Land Vehicle Navigation System Based on the Integration of Strap-Down INS and GPS

Rade Stančić and Stevica Graovac

Abstract—**The concept and results of integration of a strap-down inertial navigation system (INS) based on low-accuracy inertial sensors and the global positioning system (GPS) for the purposes of land vehicle navigation have been presented in this paper. The integration is made by an implementation of extended Kalman filter scheme, both for the initial alignment and navigation phases. Traditional integration schemes (centralized and cascaded) are basically held on the usage of high-accuracy inertial sensors. The idea behind suggested algorithm is to use low-accuracy inertial sensors and GPS as the main source of a navigation information, while the acceptable accuracy of INS is achieved by the appropriate damping of INS errors. The specified values of damping coefficients can have different influence depending on the fact whether the moving object is maneuvering or is moving with a constant velocity during the intervals of absence of GPS data. The analysis of integrated navigation system performances is made experimentally using the data acquired along the real land vehicle's trajectory and by artificial introduction of intervals of absence of GPS data on the parts characterized both by maneuver and by constant velocity, and by varying the values of error damping coefficients.**

Index Terms—**Navigation, Land vehicles, Inertial navigation, Global positioning system, Extended Kalman filter.**

I. INTRODUCTION

THE integration of heterogeneous navigation systems is a frequently used approach for the increasing of overall reliability and accuracy of navigation algorithms. One of the most popular examples nowadays consists in the integration of inertial navigation and global positioning systems. The main idea behind this approach is based on the fact that the errors separately characterizing anyone of them are not mutually correlated at all. While the GPS errors are basically due to RF channel disturbances, changes in configuration of observed satellites, occlusions of the receiver antenna, and atmospheric influences, the errors characterizing an INS are of a long periodic nature and are independent on environmental conditions. According to these facts one can expect that two systems could assist and correct each other, increasing the overall navigation system reliability and accuracy, this way. Satellite based positioning system provides more accurate information regarding the moving object's position and linear velocity in comparison to INS, especially if one considers a low-cost strap-down INS suitable for the land vehicle navigation applications. The function of such type of an INS consists in providing of navigation parameters on the intervals between consecutive GPS measurements, calculation of an object's angular orientation, and providing of the overall set of navigation parameters during the intervals of absence of GPS data. In other words, only the short term accuracy of an INS is required. While the GPS measurements are available, the estimations of INS errors are calculated and these are used for INS corrections on the intervals when GPS data are absent. Besides this function, GPS data are used during the overall system initialization and calibration also.

For the cases of middle and high-accuracy INS, there are two basic methods/schemes of INS/GPS integration: centralized and cascaded. In the case of a centralized scheme, there exists an unique INS/GPS navigation algorithm with a generalized navigation parameters error model. In the cascaded integration scheme, corrections of an INS output information are done based on GPS measurements, without any changes in navigation data processing, neither in the INS nor in the GPS part of algorithm. Wherever the set of independent sources is used, the cascaded integration scheme is preferable, allowing the choice of the system providing the most complete navigation information at a particular moment. If one wants to use the low-cost/low-accuracy INS inside this integration scheme, the problem of system initialization as well as of the on-line error estimation becomes more meaningful.

The approach used here in integration of INS and GPS is based on theoretical basis exposed in [1], [3] and [13]. The optimization of an inertial navigation algorithms based on information regarding moving object's dynamics is particularly considered in [4], followed by the analysis of a scope of applicability.

One can recognize the following main items in an attempt to design and implement the integrated INS/GPS navigation system for different applications, including the cases of automatically controlled land vehicles:

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R. Stančić is with SMATSA (Serbia and Montenegro's Air Traffic Services Agency), (e-mail: rstancic@gmail.com).

S. Graovac is with School of Electrical Engineering, University of Belgrade, Signals & Systems Department, (e-mail: graovac@etf.rs)

1. Overall system configuration (basically it is GPS + “Inertial Measurement Unit”, but sometimes without rate gyros, with addition of magnetometer, angular sensors, odometer, etc.);
2. Quality of inertial instruments and their error model parameterization (the type of instrument error models and procedures of actual parameterization);
3. Duration of the initialization/alignment phases (how complex and how long these procedures are and what could be done to make them adaptive in some way in order to reduce their duration);
4. Complexity of an integration algorithm (tight or weak coupling of navigation systems, variability of measurement error model, additional navigation state error damping, how to prepare the system for the intervals of GPS data absence,...);
5. System performances during the intervals of absence of GPS data (the existence of vehicle maneuver during these intervals).

While for some applications, [5], it was proposed to use gyro-free “dead-reckoning” configuration, our choice was to use the full strap-down navigation system as the INS part of system as in [6], having in mind that moving across a terrain in general introduces meaningful pitch and roll angles and that gravity components affect the acceleration measurements. The magnetometer and two additional angular sensors have been added for the initial alignment purposes while the usage of an odometer was supposed as the alternative source of velocity data when GPS signals are absent. There is a general trend to use low-accuracy inertial instruments in these systems (mostly of MEMS type, while in our case these were of electro-mechanical type). The importance of proper error model parameterization was respected and it was done in a manner like in [7] where only strap-down INS was used for a land vehicle navigation purposes. While some authors, [8], [9], suggest the usage of adaptive Kalman filter schemes or banks of Kalman filters in order to reduce the time needed to obtain good estimates of instrument error models during the initial alignment phase, our approach was to use “regular” EKF (the same as in navigation mode) because the experiments have shown that the required duration of this process was still acceptable. Regarding the type of integration scheme we have chosen the modified cascaded one as the type allowing full separation of navigation systems. The quality of KF estimation during the integrated navigation phase is generally monitored and in some examples, [10], the adaptive tuning of EKF is suggested. In our case we have used the simple idea to monitor the values of residuals and to use the predicted values of outputs instead of actual measurements if they are of “outlier” type. The very important task of preparing of a system for the prediction phase when GPS data are absent, some authors solve by application of artificial neural networks, [11], in order to make the model of navigation state error as accurate as possible. On the other hand, we have recognized the fact of vehicle maneuvering as the most important one characterizing the dynamic environment at the moment when GPS data are lost and suggested the usage of odometer as the alternate source of velocity data and the adaptation of velocity error damping coefficients according to the registered level of vehicle’s maneuver, [14], [15].

II. INS/GPS INTEGRATION SCHEME

The diagram shown on Fig. 1 illustrates the INS/GPS integration scheme while the Fig. 2 illustrates the system working regimes. The main working regimes of the integrated navigation system are “INITIAL ALIGNMENT” and “NAVIGATION”. Immediately after the system start-up, the initialization procedure starts by transferring GPS data regarding the geographical longitude, latitude, and height as well as of velocity. The next step consists in the initializations of Kalman filter matrices, the initialization of the block used for corrections of deterministic errors of inertial instruments (biases, scale factor errors, non-orthogonallity, etc.), and in system preparation for the start of “INITIAL ALIGNMENT”.

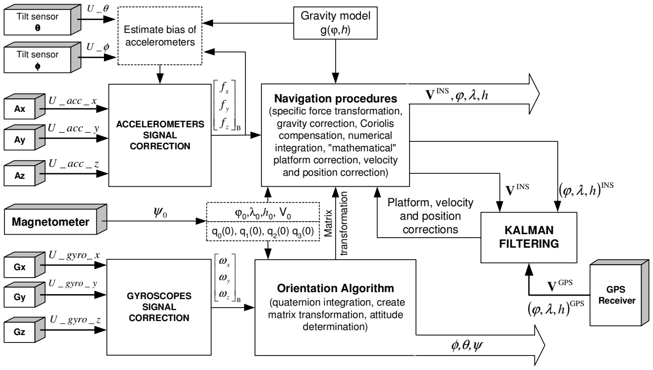

Fig. 1. Block diagram of integrated navigation system.

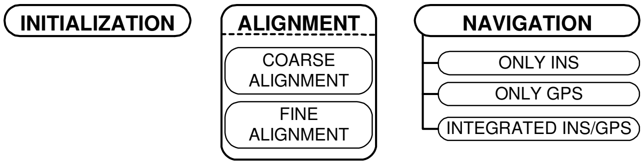

Fig. 2. Working regimes of integrated navigation system.

After the initialization is finished, the system automatically starts the first alignment step – “COARSE ALIGNMENT”. During this step the following procedures are made: coarse alignment in azimuth (using the magnetic compass), calibration of gyro drifts, horizontal alignment, initial estimation of angular attitude, determination of quaternion parameters, and calculation of transform matrix (DCM) coefficients. Using the additional angular sensors it is possible to determine the accelerometers biases also. After the “COARSE ALIGNMENT” is finished, the “FINE ALIGNMENT” starts automatically. As a result of this procedure, the following estimates are available: non-stationary components of accelerometers biases and gyro drifts, diagonal elements of covariance matrices in Kalman filter, final estimates of angular attitude, and final data for the correction block. The whole “INITIAL ALIGNMENT” phase is done in stationary conditions and for the ground vehicles its duration was of order of 5 – 10 minutes. The extended Kalman filter (EKF) used for the estimation of INS errors uses velocity deviations $\delta\mathbf{V}$ as the measurements. If the GPS works in good geometric conditions (more than four satellites available), the system works as complete INS/GPS integrated one and the differences between velocity data obtained separately by INS and GPS are used as the measurements driving EKF algorithm. If some looses of GPS data exist during this phase, EKF works in "PREDICTION" mode using the last state vector estimates obtained before the loss as inputs.

III. STRAP-DOWN INS ALGORITHM

The sampling technique used in the implementation of INS algorithm was based on the idea that the navigation tasks can be separated into two parts: Earth rotation characterized by slow dynamics, calculated with sampling interval Δt_l, and object's motion characterized by fast dynamics (determination of inertial sensors errors, forming of vectors of velocity $(\mathbf{\Delta V})$ and attitude $(\mathbf{\Delta\alpha})$ increments), calculated with sampling interval Δt_h.

The attitude determination requires the forming of matrix transforms (using direction cosines or quaternions). If the orientation of a navigation coordinate frame practically is not changed during the one calculation step, it can be considered as the inertial one. Quaternion equation representing the transformation from non-inertial (body fixed) coordinate frame and the inertial one, can be represented as the first step in calculation of a matrix transform $\mathbf{C}_\mathrm{B}^\mathrm{N}$ in the form [1]:

$$\mathbf{Q}_{k+1}^{P} = \mathbf{Q}_{k}^{F}\,\mathbf{\Delta\lambda} \tag{1}$$

where: $\mathbf{Q}^P$ - preliminary quaternion, $\mathbf{Q}^F$ - final quaternion, and $\mathbf{\Delta\lambda} = \Delta\lambda_0 + \Delta\lambda_1 i + \Delta\lambda_2 j + \Delta\lambda_3 k$ - increment of a quaternion. The transform from inertial to navigation coordinate frame is obtained on the second step represented via quaternion equation:

$$\mathbf{Q}_{k+1}^{F} = \mathbf{\Delta m}\mathbf{Q}_{k+1}^{P} \tag{2}$$

where: $\mathbf{\Delta m} = \Delta m_0 - \Delta m_1 i - \Delta m_2 j - \Delta m_3 k$ - quaternion increment representing the rotation of a navigation coordinate frame relative to the inertial one. In order to solve (1) one needs to calculate the angular increment $\mathbf{\Delta\Phi}$, given as

$$\mathbf{\Delta\Phi} = \int_{t_n}^{t_n+\Delta t_n} \boldsymbol{\omega}\,dt + \frac{1}{2}\int_{t_n}^{t_n+\Delta t_n} (\mathbf{\Phi}\times\boldsymbol{\omega})\,dt \tag{3}$$

The second right hand term in (3) introduces the correction of a coning motion that should be done more frequently than the matrix transform is calculated. There are a number of suggested algorithms of coning effect correction based on (3) and for the purposes of the actual algorithm the four-step correction algorithm suggested in [1] was used.

The equations specifying the velocity and position of an object in navigation coordinate frame (NED) can be given in the integral form as:

$$\begin{aligned} \mathbf{V}^\mathrm{N} &= \int_0^t \mathbf{f}^\mathrm{N} dt - \int_0^t [2\boldsymbol{\omega}_\mathrm{IE}^\mathrm{N} + \boldsymbol{\omega}_\mathrm{EN}^\mathrm{N}]\times\mathbf{V}^\mathrm{N} dt + \int_0^t \mathbf{g}^\mathrm{N} dt \\ \mathbf{S}^\mathrm{N} &= \int_0^t \mathbf{V}^\mathrm{N} dt \end{aligned} \tag{4}$$

where: $\mathbf{V}^\mathrm{N} = [V_N \quad V_E \quad V_D]^T$ - velocity vector, $\mathbf{S}^\mathrm{N} = [S_N \quad S_E \quad S_D]^T$ - position vector, $\mathbf{g}^\mathrm{N} = [0 \quad 0 \quad g]^T$ - gravitation vector, $\boldsymbol{\omega}_\mathrm{IE}^\mathrm{N} = [\omega_e\cos\varphi \quad 0 \quad -\omega_e\sin\varphi]^T$, vector representing Earth rotation relative to the inertial space (ω_E = 7.292115 × 10^{-5} rad/s, φ - geographic latitude), $\boldsymbol{\omega}_\mathrm{EN}^\mathrm{N} = \left[\frac{V_E}{R_P+h} \quad \frac{-V_N}{R_M+h} \quad \frac{V_E\tan\varphi}{R_P+h}\right]^T$ - vector representing the rotation of a navigation coordinate frame relative to the Earth, where:

$$R_P = \frac{a}{\left(1 - e^2\sin^2\varphi\right)^{1/2}} \qquad R_M = \frac{a\left(1-e^2\right)}{\left(1 - e^2\sin^2\varphi\right)^{3/2}} \tag{5}$$

for ellipsoid WGS-84: a = 6,378.137 km, e^2 = 0.00669438.

The first integral in (4) represents the sum of velocity increments along one calculation step as a result of transform of a specific force vector from body-fixed frame to the navigation frame (NED). The simultaneous existence of linear and angular oscillations along two perpendicular axes introduces so called sculling effect with negative influence onto the overall accuracy if it is not corrected with the frequency not high enough.

Having in minds that the Coriolis and gravitational accelerations are slowly changing, their corrections can be made with lower frequency of calculation,

$$\left(\mathbf{V}_{l+1}^\mathrm{N}\right)_{ccg} = [2\mathbf{\Omega}_\mathrm{IE}^\mathrm{N}\cdot\Delta t_l + \mathbf{\Omega}_\mathrm{EN}^\mathrm{N}\cdot\Delta t_l]\cdot(\mathbf{V}_l^\mathrm{N})_{ccg} + \mathbf{g}\cdot\Delta t_l \tag{6}$$

where: $\mathbf{\Omega}_\mathrm{IE}^\mathrm{N} = [\boldsymbol{\omega}_\mathrm{IE}^\mathrm{N}\times]$ - sqew-symmetric matrix with elements of vector $\boldsymbol{\omega}_\mathrm{IE}^\mathrm{N}$, $\mathbf{\Omega}_\mathrm{EN}^\mathrm{N} = [\boldsymbol{\omega}_\mathrm{EN}^\mathrm{N}\times]$ - sqew-symmetric matrix with elements of vector $\boldsymbol{\omega}_\mathrm{EN}^\mathrm{N}$, $\mathbf{V}_l^\mathrm{N}$ - velocity correction vector onto the l-th calculation step.

Corrected value of velocity vector is obtained as the output of INS. The object's position in NED is obtained via its integration.

IV. THE INTEGRATION ALGORITHM

The suggested INS/GPS integration algorithm was based on the assumption that inertial sensors are of low accuracy, not allowing the implementation of an autonomous INS and application of traditional centralized or cascaded integration schemes. As a result of this, the algorithm based on INS error damping is performed. This error damping is based on velocity information supplied by GPS, in order to decrease amplitudes of their oscillations, using the frequency of updating which is higher than Schuler's. Besides this, the velocity and position corrections are produced based on the velocity and position estimates obtained by EKF. The integration scheme is shown on Fig. 3.

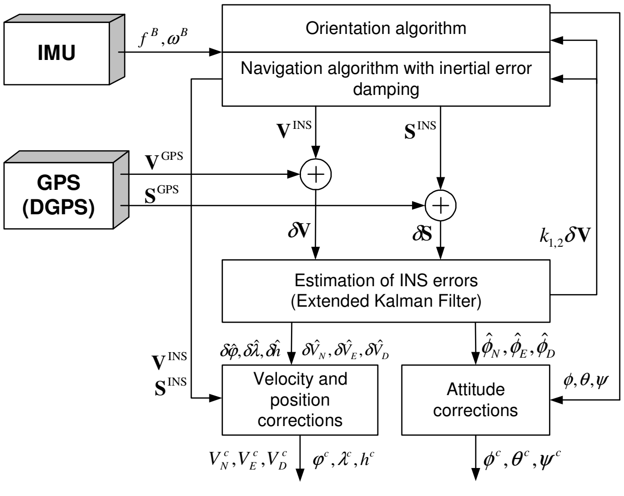

Fig. 3. Integration algorithm.

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The choice of constant coefficients k_1 and k_2 in control signals is based on the compromise between two opposite requirements: the small navigation system static error on one side, and the required system bandwidth relative to gyro errors, on the other. Large values of control signals enable the fast damping of velocity errors but makes the system bandwidth higher introducing the higher influence of high-frequency components of gyro drift onto the overall system accuracy. This fact is more serious in cases of low-accuracy inertial sensors. As a result of this, the natural frequency ω_0 of un-damped oscillations in INS should be chosen as low as acceptable. The lowest one is obtained from the condition specified in [1]:

$$\omega_0 > 1.46 \frac{\omega_{E,N}^{dr}}{|\Phi_{N,E}|} \tag{7}$$

where: $|\Phi_{N,E}|$ - orientation error of "computed" platform in linear zone $\left(|\Phi_N|, |\Phi_E| < 2° - 3°\right)$ and $\omega_{E,N}^{dr}$ - projections of gyro drifts onto the east and north axes of NED frame.

Based on INS error analyses it was shown in [1] that the following values of coefficients k_1 and k_2 are suggestible:

$$k_1 = 2\xi\omega_0 \qquad k_2 = \omega_0^2 / g, \tag{8}$$

where: ξ - damping coefficient and ω_0 – natural frequency from (7). According to this, the error model is now different from the standard one and can be represented as in (9), where: $\delta V_N, \delta V_E, \delta V_D$ - INS velocity errors, $\delta\varphi, \delta\lambda, \delta h$ - INS position errors, f_N, f_E, f_D - specific forces projected on NED axes, B_N, B_E, B_D - accelerometer biases, $\omega_N^{dr}, \omega_E^{dr}, \omega_D^{dr}$ - slow varying components of gyro drifts approximated by first order Markov processes, β and A – shaping filter coefficients.

$$\begin{aligned}
\delta\dot{V}_N &= -V_E \cos\varphi\left[2\omega_e + \dot{\lambda}\sec^2\varphi\right]\cdot\delta\varphi \\
&\quad + \left[\frac{V_E\dot{\lambda}\sin\varphi}{R_P + h} - \frac{V_D\dot{\varphi}}{R_M + h}\right]\cdot\delta h + \frac{V_D}{\mathrm{R}_M + h}\delta V_N \\
&\quad - 2\left(\omega_e + \dot{\lambda}\right)\sin\varphi\cdot\delta V_E + \dot{\varphi}\delta V_D \\
&\quad - f_D\phi_E + f_E\phi_D + B_N + u_N^v \\
\delta\dot{V}_E &= \left[2\omega_e\left(V_N\cos\varphi - V_D\sin\varphi\right) + \dot{\lambda}V_N\sec\varphi\right]\cdot\delta\varphi \\
&\quad - \frac{\dot{\lambda}}{R_P + h}\left[V_D\cos\varphi + V_N\sin\varphi\right]\cdot\delta h \\
&\quad + \left(2\omega_e + \dot{\lambda}\right)\sin\varphi\cdot\delta V_N + \frac{1}{R_P + h}\left[V_D + V_N tg\,\varphi\right]\cdot\delta V_E \\
&\quad + \left(2\omega_e + \dot{\lambda}\right)\cos\varphi\cdot\delta V_N + f_D\phi_N - f_N\phi_D + B_E + u_E^v \\
\delta\dot{V}_D &= 2\omega_e V_E\sin\varphi\cdot\delta\varphi \\
&\quad + \left[\frac{V_N}{R_M + h}\dot{\varphi} + \frac{V_E}{R_P + h}\dot{\lambda}\cos\varphi + (k-2)\frac{g}{R_e}\right]\cdot\delta h \\
&\quad - 2\dot{\varphi}\cdot\delta V_N - 2\left(\omega_e + \dot{\lambda}\right)\cos\varphi\cdot\delta V_E \\
&\quad - f_E\phi_N + f_N\phi_E + B_D \\
\dot{\phi}_N &= -\omega_e\sin\varphi\cdot\delta\varphi - \frac{\dot{\lambda}}{R_P + h}\cos\dot{\varphi}\delta h + \frac{1}{R_P + h}\delta V_E \\
&\qquad - \left(\omega_e + \dot{\lambda}\right)\sin\varphi\cdot\phi_E + \dot{\varphi}\phi_D - \omega_N^{dr} + u_E^{\phi} \\
\dot{\phi}_E &= \frac{\dot{\varphi}}{R_M + h}\delta h_i - \frac{1}{R_M + h}\delta V_N + \left(\omega_e + \dot{\lambda}\right)\sin\varphi\cdot\phi_N \\
&\qquad + \left(\omega_e + \dot{\lambda}\right)\cos\varphi\cdot\phi_D - \omega_E^{dr} + u_N^{\phi} \\
\dot{\phi}_D &= -\left(\omega_e\cos\varphi + \dot{\lambda}\sec\varphi\right)\cdot\delta\varphi + \frac{\dot{\lambda}}{R_P + h}\sin\varphi\cdot\delta h \\
&\qquad - \frac{tg\,\varphi}{R_P + h}\delta V_E - \dot{\varphi}\phi_N - \left(\omega_e + \dot{\lambda}\right)\cos\varphi\cdot\phi_E - \omega_D^{dr} \\
\dot{\omega}_N^{dr} &= -\beta\omega_N^{dr} + A\sqrt{2\beta}\cdot w(t) \\
\dot{\omega}_E^{dr} &= -\beta\omega_E^{dr} + A\sqrt{2\beta}\cdot w(t) \\
\dot{\omega}_D^{dr} &= -\beta\omega_D^{dr} + A\sqrt{2\beta}\cdot w(t) \\
\delta\dot{\varphi} &= -\frac{\dot{\varphi}}{R_M + h}\delta h + \frac{1}{R_M + h}\delta V_N \\
\delta\dot{\lambda} &= \dot{\lambda}tg\,\varphi\cdot\delta\varphi - \frac{\dot{\lambda}}{R_P + h}\delta h + \frac{1}{\left(R_P + h\right)\cos\varphi}\delta V_E \\
\delta\dot{h} &= -\delta V_D \\
\dot{B}_N &= 0 \\
\dot{B}_E &= 0 \\
\dot{B}_D &= 0
\end{aligned} \tag{9}$$

Control signals $u_N^v, u_E^v, u_N^g, u_E^g$ are represented as:

$$\begin{aligned} u_N^v &= -k_1 \delta\hat{V}_N \quad & u_E^v &= -k_1 \delta\hat{V}_E \\ u_N^\phi &= -k_2 \delta\hat{V}_E \quad & u_E^\phi &= k_2 \delta\hat{V}_N \end{aligned} \tag{10}$$

where: $\delta\hat{V}_N, \delta\hat{V}_E$ - the estimates of velocity errors in north and east directions.

Using the error model (9), the EKF state vector is of order fifteen. The differences in velocities and positions obtained via INS and GPS separately are used as the measurements supplied to the EKF algorithm. The estimates of velocity and position errors are obtained from:

$$\begin{aligned} \hat{\mathbf{x}}_k^+ &= \mathbf{\Phi}_k \hat{\mathbf{x}}_{k-1}^+ + \mathbf{L}\mathbf{u}_k + \\ &+ \mathbf{K}_k \left(\mathbf{z}_k - \mathbf{H}_k \mathbf{\Phi}_k \hat{\mathbf{x}}_{k-1}^+ - \mathbf{H}_k \mathbf{L}\mathbf{u}_k \right), \end{aligned} \tag{11}$$

where: **L** – gain matrix multiplying control signals, **u** – vector of control signals.

In order to overcome the possible problems during the measurement process, the monitoring of following parameter was introduced:

$$Shock = \left(\mathbf{z}_k - \mathbf{H}_k \mathbf{x}_k^- \right)^T \left(\mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T + \mathbf{R}_k \right) \left(\mathbf{z}_k - \mathbf{H}_k \mathbf{x}_k^- \right) \tag{12}$$

where: $\mathbf{x}_k^-$ - extrapolated value of the state vector. If the value of *Shock* parameter is greater than the specified threshold the extrapolated value of system state vector is used as the filter output instead of using the actual measurements for the estimation. The estimates of velocity errors, position errors, and of the angular orientation of the "computed" platform are introduced into the navigation algorithm step by step. Velocity corrections are made in two steps. The first one consists in "correction of a computed platform":

$$\begin{aligned} V_{\mathrm{N}}^c &= V_{\mathrm{N}}^{INS} - g\hat{\Phi}_{\mathrm{E}} \\ V_{\mathrm{E}}^c &= V_{\mathrm{E}}^{INS} + g\hat{\Phi}_{\mathrm{N}} \end{aligned} \tag{13}$$

where: $\hat{\Phi}_{\mathrm{N}}, \hat{\Phi}_{\mathrm{E}}$ - the estimates of angular errors of "computed" platform. Velocity components are corrected on the second step using the estimates of velocity errors:

$$\begin{aligned} V_{\mathrm{N}}^{cc} &= V_{\mathrm{N}}^c - \delta\hat{V}_{\mathrm{N}} \\ V_{\mathrm{E}}^{cc} &= V_{\mathrm{E}}^c - \delta\hat{V}_{\mathrm{E}} \\ V_{\mathrm{D}}^{cc} &= V_{\mathrm{D}}^{INS} - \delta\hat{V}_{\mathrm{D}} \end{aligned} \tag{14}$$

where: $\delta\hat{V}_{\mathrm{N}}, \delta\hat{V}_{\mathrm{E}}, \delta\hat{V}_{\mathrm{D}}$ - velocity error estimates as EKF outputs.

Corrections of position components are done as:

$$\begin{aligned} \varphi^c &= \varphi^{INS} - \delta\hat{\varphi} \\ \lambda^c &= \lambda^{INS} - \delta\hat{\lambda} \\ h^c &= h^{INS} - \delta\hat{h} \end{aligned} \tag{15}$$

where: $\delta\hat{\varphi}, \delta\hat{\lambda}, \delta\hat{h}$ - estimates of geographical latitude, longitude, and height, obtained as the outputs of EKF.

During the intervals of absence of reliable GPS data the system works in "PREDICTION" mode when the last state vector estimates before the loss of GPS data are used. Kalman filter gain matrix is equal to zero matrix then (**K** = 0). Error damping control signals are produced using the measurements of odometer as an alternate sensor.

V. PROTOTYPE OF AN INTEGRATED INS/GPS SYSTEM

The prototype of an integrated INS/GPS system is based on usage of three mechanical rate gyros (Sfim I1426, of a range up to 20°/s) and three linear accelerometers (Sfim JT21, of a range up to 20m/s$^{2)}$. Sampling frequency of inertial sensor data is 100 Hz. Two additional angular sensors (Sfim JC30, ±30°) are used for initial alignment purposes. GPS receiver is of "μ-blox GPS-PS1E" type (S/A code, working frequency L1, updating frequency 1Hz, declared accuracy – 5m). Components of prototype are shown on Fig. 4.

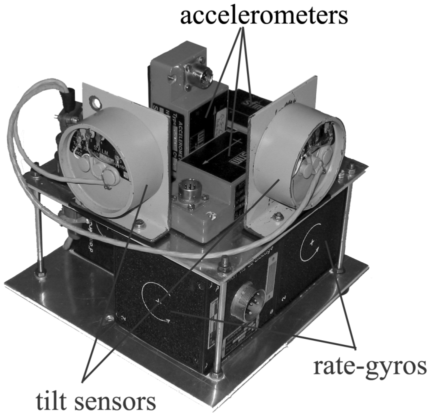
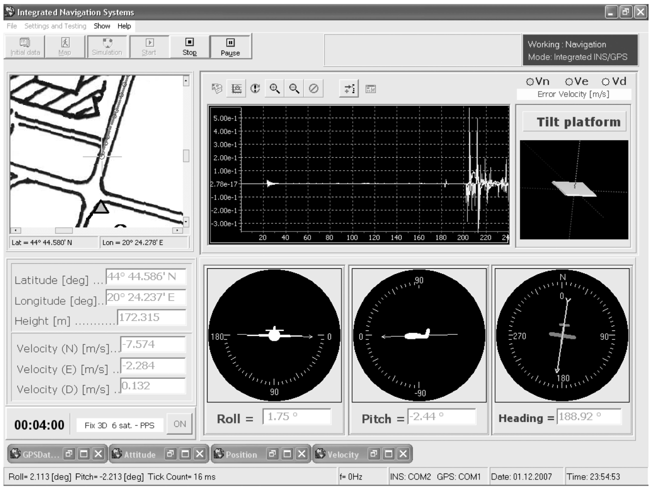


Fig. 4. Prototype of inertial measurement unit (IMU).

The specialized software support has been made [12] for the purposes of INS/GPS system development. It enables the work of system both in "INITIAL ALIGNMENT" and "NAVIGATION" phases. The basic display is shown on Fig. 5.



Working : Navigation
Mode: Integrated INS/GPS

Lat = 44° 44.580' N
Lon = 20° 24.278' E

Latitude [deg] ... 44° 44.586' N
Longitude [deg].. 20° 24.237' E
Height [m] 172.315
Velocity (N) [m/s].. -7.574
Velocity (E) [m/s] .. -2.284
Velocity (D) [m/s] .. 0.132

00:04:00
Fix 3D 6 sat. - PPS

Roll = 1.75 °
Pitch = -2.44 °
Heading = 188.92 °

Roll= 2.113 [deg] Pitch= -2.213 [deg] Tick Count= 16 ms
f= 0Hz
INS: COM2 GPS: COM1
Date: 01.12.2007
Time: 23:54:53

Fig. 5. The basic screen.

VI. EXPERIMENTAL VERIFICATION OF INS/GPS SYSTEM

Two types of experiments have been arranged in order to verify the accuracy of integrated INS/GPS system. The first one regards to laboratory tests of inertial sensors and the whole INS part of system.

The second phase consisted in tests where the prototype was mounted on the car moving along accurately pre-specified trajectory.

The tests of inertial sensors and whole INS part used in order to estimate gyro and accelerometer errors as well as parameters of sensors stochastic models. These data are used for inertial sensor calibration and the initialization of covariance matrices of EKF. These tests were consisting from three procedures. The biases and scale factor errors of inertial sensors are determined during the first one, while the platform orientation errors are determined during the second one. The third procedure was related to the estimation of sensors stochastic models using Allan dispersion and autocorrelation function. It was possible this way to determine the dispersions of separate noise components as well as to distinguish the dominant ones.

Test platform "CARCO" T-922" was used for these purposes, and Table 1. summarizes the results of error parameter estimations.

The accelerometer error parameters have been obtained by averaging on the 15 min interval. The rate gyro parameters are determined during oscillatory motion of the test platform with ±1°/s amplitude.

The analysis of stochastic models of inertial sensor errors have been done in stationary regime. Fig. 6. illustrates the square root of Allan variance for accelerometers, and dispersions of different noise types for all used inertial sensors are summarized in Table 2.

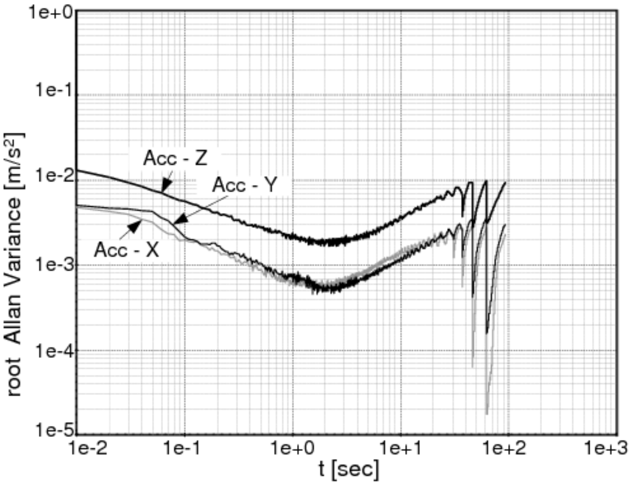


Fig. 6. Square root of Allan variance for accelerometers.

During the second phase of testing, the prototype of INS/GPS navigation system have been mounted on a moving car. The position providing continuous GPS availability was chosen for these field tests. There were a number of check-points (CP) along the trajectory where geographical coordinates had been previously determined via DGPS. The test trajectory is shown on Fig. 7. Initial alignment was done on CP-4 using the magnetometer as the external azimuth sensor.

TABLE I
INERTIAL SENSORS' BASIC ERROR MODEL PARAMETERS

accelerometer	bias [m/s^2]	scale factor error
x	-7.17×10^{-3}	-1.03×10^{-3}
y	7.506×10^{-3}	-4.49×10^{-3}
z	8.25×10^{-2}	-5.88×10^{-3}
rate gyro	drift [rad/s]	scale factor error
x	9×10^{-3}	-6.493×10^{-3}
y	5.075×10^{-3}	-4.99×10^{-3}
z	6.515×10^{-3}	1.72×10^{-2}

TABLE II
INERTIAL SENSORS' STOCHASTIC ERROR MODEL PARAMETERS

accelerometer	white noise [m/s/√s]	random walk [m/s^2/√s]
x	6.14×10^{-4}	6.48×10^{-4}
y	7.34×10^{-4}	5.73×10^{-4}
z	2.18×10^{-3}	1.94×10^{-3}
rate gyro	white noise [°/√s]	random walk [°/s/√s]
x	9.79×10^{-4}	8.4×10^{-3}
y	1.3×10^{-2}	8.71×10^{-3}
z	7.9×10^{-4}	-

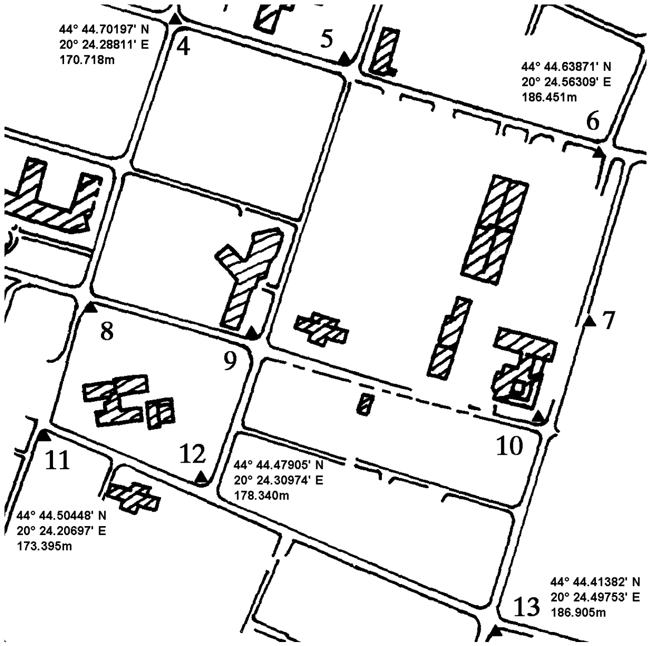


Fig. 7. Test trajectory with check-points.

One among these tests was chosen for further illustrations here. Acquisition of the inertial sensor data was made with f_{si} = 100Hz while GPS updating frequency was f_{ss} = 1Hz. The number of available satellites have been more than four, except in interval 320 – 340 s when only two of them were available. The value of satellite geometric factor PDOP was less than 4. Angular receiver mask was set to 5°, while abrupt changes in GPS data have been prevented by the procedure for their filtering.

During the overall 9.5 min interval, the system worked 180s in the "INITIAL ALIGNMENT" regime while the remaining 6.5 min worked in "NAVIGATION" regime. Car dynamics are illustrated on Fig. 8. via diagrams of specific force profiles along *x* and *y* axes of body fixed coordinate frame.

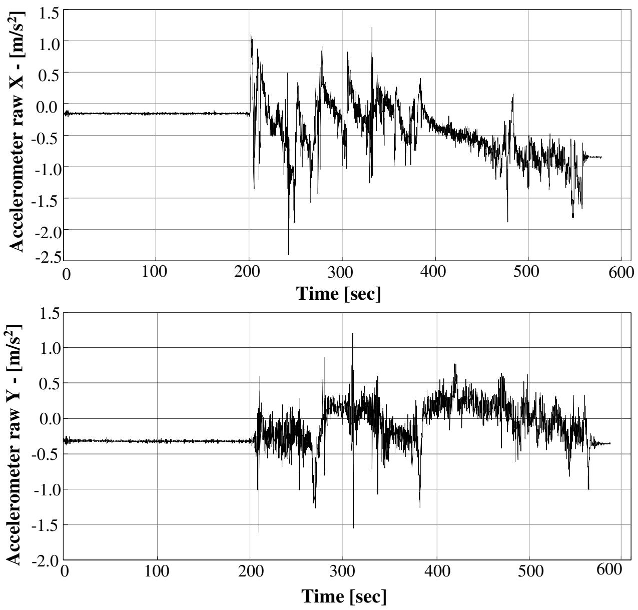


Fig. 8. Specific forces along *x* and *y* axes of body fixed coordinate frame.

Fig. 9. illustrates object's trajectory. Circular symbols are used to show GPS position data, while the linear curve represents the outputs of INS/GPS system. North and East velocity profiles are shown on Fig. 10.

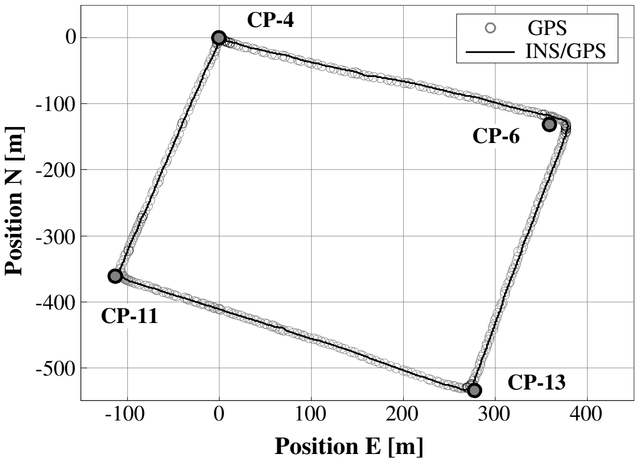


Fig. 9. GPS and INS/GPS test trajectory.

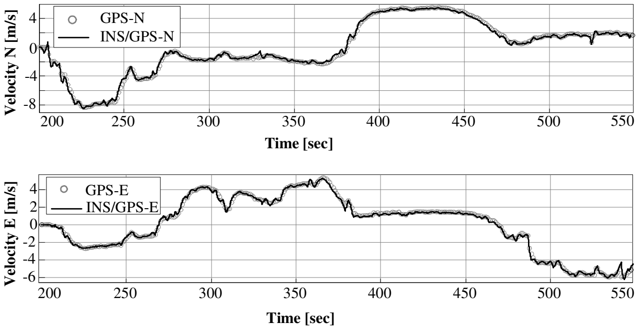


Fig. 10. GPS and INS/GPS velocity profiles.

Having in minds that the main advantage of the navigation integration concept consists in the availability of reliable navigation data during the intervals of absence of GPS information, the following tests have been arranged in order to verify system performances in such cases. The intervals of absence of GPS data have been introduced artificially in off-line analyses. The GPS data existing in reality during these intervals were used as a reference. Two particular intervals have been chosen in order to analyze the system performances depending on the fact whether the car is moving with constant velocity or is accelerating. During the first interval ([285 – 305] s) the car was moving with variable velocity, while during the second one ([418 – 438] s) it was moving with approximately constant one.

The integrated INS/GPS system worked in "PREDICTION" mode during these two intervals. North velocity profiles have been shown now on Fig. 11. It is obvious that the accuracy of integrated system is affected by the car acceleration in the first interval (maximal position error of 36 m) in comparison to the second interval when it was moving with approximately constant velocity (maximal position error of 15 m). The main reason for these differences is in the fact that non-stationary error components (non-alignment in azimuth, accelerometer scale factor error, non-orthogonality of sensors) are strongly dependent on object's dynamics.

Higher values of velocity error damping coefficients can be used now in order to improve the overall accuracy during the intervals of GPS data absence. It reduced maximal position error to 25 m in the first interval and to 10 m during the second one. The trajectories shown on Fig. 12. illustrate this case. The choice of higher values for coefficients k_1 and k_2 in (8) reduces the velocity and position errors for such cases but makes the system bandwidth larger with some disadvantages regarding the overall influence of gyro drift high frequency contents in general.

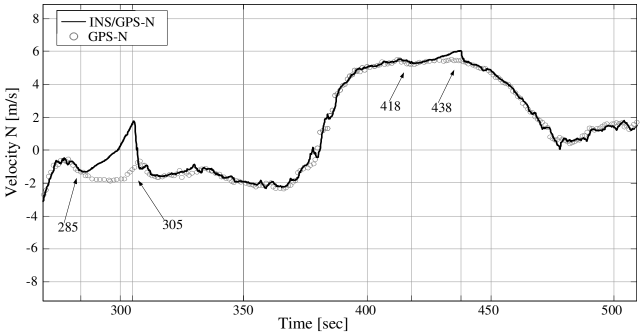


Fig. 11. GPS and INS/GPS velocity profiles for the cases of absence of GPS data.

In order to keep the acceptable accuracy for both cases (with or without GPS data) the values of damping coefficients should change according to this information. Table 3. illustrates position and velocity RMS errors in the intervals of absence of GPS data for two different values of damping coefficient k_2.

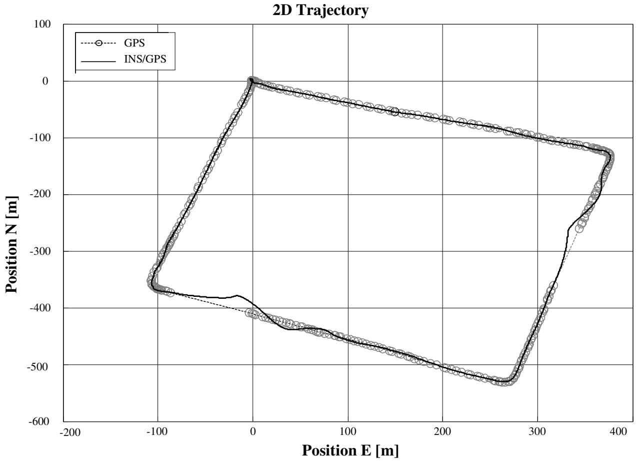


Fig. 12. GPS and INS/GPS trajectories for the cases of absence of GPS data and for strong damping of INS errors

TABLE III
POSITION AND VELOCITY RMS ERRORS

position (RMS) [m]		velocity (RMS) [m/s]		κ_1	κ_2	interval [s]
N	E	V_N	V_E			
6.917	10.279	1.054	0.593	20.5	12.35	285 – 305
15.411	12.668	1.309	0.653	20.5	10.35	
4.662	1.368	0.280	0.366	20.5	12.35	418 – 438
5.7494	5.07	0.428	0.494	20.5	10.35	

VII. CONCLUSION

The main purpose of this work was to demonstrate possibility of implementation of an integrated low-cost strap-down INS and the GPS for the land vehicle application. An extended Kalman filter scheme for the optimal estimation of navigation state errors as well as for inertial instrument errors was used, based on the measurements consisting in differences in velocity and position vectors obtained from INS and GPS separately. Additional error damping was introduced in order to overcome the fact that the inertial instruments were of low accuracy. After the laboratory work consisting in IMU error model parameterization the prototype of integrated navigation system was used in ground experiments. Duration of the initialization phase was of order of three minutes. The navigation phase have shown that the integrated system worked very well (i.e. that 1 Hz GPS measurements have made the corrections of the INS output very precisely). However, the main advantage of integration scheme should be verified when the GPS data are absent in some longer intervals. The main results of these tests for 20s long intervals of GPS data absence have indicated that the values of damping coefficients should be adapted according to the fact whether the vehicle is maneuvering or not at the moment of losing the valid GPS data. Generally, these coefficients should keep the values suggested in literature as the optimal ones whenever the GPS data are present. If the vehicle is maneuvering during the intervals of absence of GPS data their values should be increased. In spite of the fact that the overall bandwidth is increased this way and that high frequency components of IMU errors would have the higher influence, this is beneficial because the errors dependent on vehicle dynamics are dominant then and their influence should be attenuated basically. The work in progress consists in miniaturization of INS system using MEMS inertial sensors and in further modification of the integration algorithm based on more precise adaptation of error damping coefficients according to the measured value of vehicle acceleration during the intervals of GPS data absence.

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