INS/GPS SYNERGIC NAVIGATOR WITH KALMAN FILTERING

Dragos George SANDU[1], Ion FUIOREA[2], Teodor Lucian GRIGORIE[3]

This paper proposes a synergetic architecture navigator, the combined statistical navigation data from GPS and those obtained from a strap-down inertial navigator. After highlighting the inertial navigator equations governing the functioning of the model error and its deduction is exposed Kalman filter implementation for integrating INS / GPS. It aims at estimating error positioning, speed and attitude INS using navigation solutions to this system and the GPS system and linearized model error of INS.

Navigator synergistic INS/GPS model is implemented in a Matlab/Simulink model, which is tested experimentally using simultaneously acquired data from a GPS module and a miniaturized inertial measurement unit consisting of two gyro and accelerometric triads with MEMS sensors, both on board of a test vehicle.

1. Introduction

In recent decades have been developed and there have been a number of trends to develop independent navigation systems or integrated configurations necessary in the conduct of navigation applications in different environments, closed or open [1], [2]. In the first phase the goal was to develop stand – alone navigator, but the complexity of new applications requiring for complex navigators, led to the search for solutions for real – time monitoring of kinematic parameters of various types of vehicles. Over time, navigation applications occupied an area increasingly larger, extending from the sea, they began to aerospace, to robotics, the vehicle positioning applications, but also applications involves monitoring a human user in various military actions, civil protection (rescue in the event of natural disasters and calamities) or medical (people with disabilities). Spearheading this technology represents but aerospace applications, navigation systems currently being extended to the air traffic control systems or terrestrial monitoring board positions and velocities of vehicles in traffic nearby.

As a concept, developed navigators were initially based on independent systems, their architecture is derived from the merger of two or more systems of this type, generally with different operating principles. Also useful for seafarers craft suffered a metamorphosis as a concept, from equipment to provide additional information became undesirable equipment [1], [2].

[1] Flight Test Eng., Research and Flight Test Center, Craiova, Romania
[2] Prof. Eng., General Manager STRAERO S.A., Bucharest, Romania
[3] Assoc. Prof. Eng., University of Craiova, Faculty of Electrical Engineering, Craiova, Romania

Obtaining a robust and accurate navigator who faces different challenges of navigation applications in the same structure involves the integration of two or more navigation systems based on different methods of position determination. Precision Square seafarers currently offers a wide variety of synergistic architectures based on Kalman filter navigation data provided by GPS and inertial systems [2], [3], [4], [5], [6].

In this paper is proposed such a synergetic architecture, combining the statistical navigation data from GPS and inertial obtained from an IMU system.

2. Dynamic equations of the Strap-Down inertial navigator

Considered in determining the reference of the navigation algorithm are local horizontal reference frame NED, noted below with index l, ECEF reference frame, denoted by the index P, and vehicle related reference frame SV, denoted by the index v. Dynamic equations characterizing the resulting inertial navigator form [6], [7], [8], [9], [10]

$$\begin{pmatrix} \dot{r}^l \\ \dot{v}^l \\ \dot{R}_v^l \end{pmatrix} = \begin{pmatrix} D^{-1} \cdot v^l \\ R_v^l \cdot f^v - \left(2 \cdot \tilde{\omega}_{iP}^l + \tilde{\omega}_{Pl}^l\right) \cdot v^l + g^l \\ R_v^l \cdot (\tilde{\omega}_{iv}^v - \tilde{\omega}_{il}^v) \end{pmatrix}, \quad (1)$$

where r^l is the position vector of the vehicle (position given by coordinates, ϕ, λ and h, h - altitude vehicle relative to the reference ellipsoid, ϕ - latitude, λ - longitude, v^l - vehicle velocity vector components NED reference system (v_N, v_E și v_D), f^v reflects accelerometer readings, R_v^l it is managing the transformation matrix SV → NED, $\tilde{\omega}_{iP}^l$ - skew symmetric matrix components characterizing the speed of rotation around its axis Earth in referential NED, $\tilde{\omega}_{Pl}^l$ - skew symmetric matrix characterizing the angular velocity of transport (NED reference system relative to the reference system ECEF) expressed in terms of the variation of latitude and longitude coordinates expressed in NED, $\tilde{\omega}_{iv}^v$ - skew symmetric matrix characterizing the absolute angular velocity components in SV reference frame own axis (reflecting gyro measurement) $\tilde{\omega}_{il}^v$ - skew symmetric matrix characterizing the absolute angular velocity components in NED translated in SV axes, g^l – gravitational acceleration components in NED,

$$D^{-1} = \begin{pmatrix} \frac{1}{R_m + h} & 0 & 0 \\ 0 & \frac{1}{(R_n + h)\cos\phi} & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad (2)$$

$$R_v^l = \begin{pmatrix} \cos\theta\cos\psi & -\cos\varphi\sin\psi + \sin\varphi\sin\theta\cos\psi & \sin\varphi\sin\psi + \cos\varphi\sin\theta\cos\psi \\ \cos\theta\sin\psi & \cos\varphi\cos\psi + \sin\varphi\sin\theta\sin\psi & -\sin\varphi\cos\psi + \cos\varphi\sin\theta\sin\psi \\ \sin\theta & \sin\varphi\cos\theta & \cos\varphi\cos\theta \end{pmatrix}, \quad (3)$$

$$\omega_{iP}^{l} = (\omega_P \cos\phi\,, \quad 0, \quad -\omega_P \sin\phi)^T, \tag{4}$$

$$\omega_{Pl}^{l} = \left(\frac{v_E}{R_n + h}, \quad -\frac{v_N}{R_m + h}, \quad -\frac{v_E}{R_n + h} \cdot \tan\phi\right)^T, \tag{5}$$

$$v^l = (v_N, \quad v_E, \quad v_D)^T, \tag{6}$$

$$\omega_{il}^{v} = R_l^v \cdot \omega_{il}^{l} \tag{7}$$

$$R_l^v = (R_v^l)^{-1} \tag{8}$$

$$\begin{aligned}\omega_{il}^{l} &= \omega_{iP}^{l} + \omega_{Pl}^{l}\\ &= \left(\omega_P \cos\phi + \frac{v_E}{R_n + h}, \quad -\frac{v_N}{R_m + h}, \quad -\omega_P \sin\phi - \frac{v_E}{R_n + h} \cdot \tan\phi\right)^T.\end{aligned} \tag{9}$$

ψ - yaw angle, θ – pitch angle, φ – roll angle, R_m - beam ellipsoid after meridian, R_n - after the first vertical ellipsoid radius and ω_P - rotational speed of the Earth around its axis ($\omega_P = 7.29121158 \cdot 10^{-5}\text{rad/s}$).

3. Error model of strap – down inertial navigator

In determining the equations modeling the inertial navigator errors is based on the theory of small perturbations, the equations of nonlinear system of differential equations described above [9], [11], [12], [13].

Whether $\delta r^l, \delta v^l$ and δg^l perturbations position, speed and acceleration of gravity. It follows that the calculated values of position, velocity, attitude and gravity have expressions

$$\begin{cases}\hat{r}^l = r^l + \delta r^l,\\ \hat{v}^l = v^l + \delta v^l,\\ \hat{R}_v^l = (I - \tilde{e}^l) \cdot R_v^l\,,\\ \gamma^l = g^l + \delta g^l;\end{cases} \tag{10}$$

$\tilde{e}^l$ − skew symmetric matrix for attitude errors, γ − normal gravity vector,

$$\tilde{e}^l = \left(e^l \times\right) = \begin{pmatrix} 0 & -e_D & e_E\\ e_D & 0 & -e_N\\ -e_E & e_N & 0\end{pmatrix}. \tag{11}$$

Disturbing the first equation of the system is obtained mathematical form

$$\delta\dot{r}^l = F_{rr} \cdot \delta r^l + F_{rv} \cdot \delta v^l, \tag{12}$$

where

$$F_{rr} = \begin{pmatrix} 0 & 0 & -\dfrac{v_N}{(R_m + h)^2}\\ \dfrac{v_E \cdot \sin\phi}{(R_n + h) \cdot \cos^2\phi} & 0 & \dfrac{-v_E}{(R_n + h)^2 \cdot \cos\phi}\\ 0 & 0 & 0\end{pmatrix} \tag{13}$$

$$F_{rv} = \begin{pmatrix} \dfrac{1}{R_m + h} & 0 & 0 \\ 0 & \dfrac{1}{(R_n + h) \cdot \cos\phi} & 0 \\ 0 & 0 & -1 \end{pmatrix}. \tag{14}$$

A second dynamic equation that characterizes the speed is given by

$$\dot{v}^l = R_v^l \cdot f^v - \left(2 \cdot \widetilde{\omega}_{iP}^l + \widetilde{\omega}_{Pl}^l\right) \cdot v^l + g^l. \tag{15}$$

The calculated results such as velocity derivative

$$\hat{\dot{v}}^l = \hat{R}_v^l \cdot \hat{f}^v - \left(2 \cdot \hat{\widetilde{\omega}}_{iP}^l + \hat{\widetilde{\omega}}_{Pl}^l\right) \cdot \hat{v}^l + \gamma^l, \tag{16}$$

and the disturbed form is

$$\begin{aligned} \dot{v}^l + \delta\dot{v}^l = \left(I - \tilde{e}^l\right) \cdot R_v^l \cdot (f^v + \delta f^v) - \\ -\left(2 \cdot \widetilde{\omega}_{iP}^l + \widetilde{\omega}_{Pl}^l + 2 \cdot \delta\widetilde{\omega}_{iP}^l + \delta\widetilde{\omega}_{Pl}^l\right) \cdot \left(v^l + \delta v^l\right) + g^l + \delta g^l. \end{aligned} \tag{17}$$

Expression of δv^l resulting form

$$\delta\dot{v}^l = F_{vr} \cdot \delta r^l + F_{vv} \cdot \delta v^l + (f^l \times)e^l + R_v^l \cdot \delta f^v, \tag{18}$$

where

$$F_{vr} = \begin{pmatrix} -2 \cdot v_E \cdot \omega_P \cdot \cos\phi - \dfrac{v_E^2}{(R_n + h) \cdot \cos^2\phi} & 0 & -\dfrac{v_D \cdot v_N}{(R_m + h)^2} + \dfrac{v_E^2 \cdot \tan\phi}{(R_n + h)^2} \\ 2 \cdot v_N \cdot \omega_P \cdot \cos\phi - 2 \cdot v_D \cdot \omega_P \cdot \sin\phi + \dfrac{v_E \cdot v_N}{(R_n + h) \cdot \cos^2\phi} & 0 & -\dfrac{v_D \cdot v_E}{(R_n + h)^2} - \dfrac{v_N \cdot v_E \cdot \tan\phi}{(R_m + h)^2} \\ 2 \cdot v_E \cdot \omega_P \cdot \sin\phi & 0 & \dfrac{v_E^2}{(R_n + h)^2} + \dfrac{v_N^2}{(R_m + h)^2} - \dfrac{2 \cdot \gamma_0 \cdot R_m \cdot R_n}{\left(\sqrt{R_m \cdot R_n} + h\right)^3} \end{pmatrix} \tag{19}$$

$$F_{vv} = \begin{pmatrix} \dfrac{v_D}{R_m + h} & -2 \cdot \omega_P \cdot \sin\phi - \dfrac{2 \cdot v_E \cdot \tan\phi}{R_n + h} & \dfrac{v_N}{R_m + h} \\ 2 \cdot \omega_P \cdot \sin\phi + \dfrac{v_E \cdot \tan\phi}{R_n + h} & \dfrac{v_D + v_N \cdot \tan\phi}{R_n + h} & 2 \cdot \omega_P \cdot \cos\phi + \dfrac{v_E}{R_n + h} \\ -\dfrac{2v_N}{R_m + h} & -2 \cdot \omega_P \cdot \cos\phi - \dfrac{2v_E}{R_n + h} & 0 \end{pmatrix} \tag{20}$$

Attitude dynamic equation characterizing the navigator is

$$\dot{R}_v^l = R_v^l \cdot (\widetilde{\omega}_{iv}^v - \widetilde{\omega}_{il}^v), \tag{21}$$

with variant as the form

$$\dot{\hat{R}}_v^l = \hat{R}_v^l\left(\hat{\widetilde{\omega}}_{iv}^v - \hat{\widetilde{\omega}}_{il}^v\right). \tag{22}$$

Also

$$\dot{\tilde{e}}^l = -R_v^l \cdot (\delta\widetilde{\omega}_{iv}^v - \delta\widetilde{\omega}_{il}^v) \cdot R_l^v, \tag{23}$$

namely

$$(\dot{e}^l \times) = -R_v^l \cdot \left((\delta\omega_{iv}^v - \delta\omega_{il}^v) \times\right) \cdot R_l^v. \tag{24}$$

After reaching reorganization formula

$$\dot{e}^l = -R_v^l \cdot (\delta\omega_{iv}^v - \delta\omega_{il}^v), \tag{25}$$

$\delta\omega_{iv}^v -$ errors of gyro readings

Absolute angular velocity components in local horizontal axes are given by the relation

$$\omega_{il}^l = \begin{pmatrix} \omega_P \cdot \cos\phi + \dfrac{v_E}{R_n + h} \\ -\dfrac{v_N}{R_m + h} \\ -\omega_P \cdot \sin\phi - \dfrac{v_E \cdot \tan\phi}{R_n + h} \end{pmatrix} = \begin{pmatrix} OM_x \\ OM_y \\ OM_z \end{pmatrix}, \tag{26}$$

which disturbed leads to formula

$$\delta\omega_{il}^l = \delta\Omega_{inr} \cdot \delta r^l + \delta\Omega_{inv} \cdot \delta v^l, \tag{27}$$

In the

$$\delta\Omega_{inr} = \begin{pmatrix} -\omega_P \cdot \sin\phi & 0 & -\dfrac{v_E}{(R_n + h)^2} \\ 0 & 0 & \dfrac{v_N}{(R_m + h)^2} \\ -\omega_P \cdot \cos\phi - \dfrac{v_E}{(R_n + h) \cdot \cos^2\phi} & 0 & \dfrac{v_E \cdot \tan\phi}{(R_n + h)^2} \end{pmatrix} \tag{28}$$

and

$$\delta\Omega_{inv} = \begin{pmatrix} 0 & \dfrac{1}{R_n + h} & 0 \\ -\dfrac{1}{R_m + h} & 0 & 0 \\ 0 & -\dfrac{\tan\phi}{R_n + h} & 0 \end{pmatrix}. \tag{29}$$

So, $\dot{e}^l$ is it becomes

$$\dot{e}^l = F_{er} \cdot \delta r^l + F_{ev} \cdot \delta v^l - \left(\omega_{il}^l \times\right) e^l - R_v^l \cdot \delta\omega_{iv}^v, \tag{30}$$

where

$$\begin{aligned} F_{er} &= \delta\Omega_{inr}, \\ F_{ev} &= \delta\Omega_{inv}. \end{aligned} \tag{31}$$

4. Implementation of Kalman filter for INS/GPS integration

The linearized error previously obtained, it may be made in the form of

$$\dot{\mathbf{x}} = \mathbf{A} \cdot \mathbf{x} + \mathbf{G} \cdot \mathbf{w}, \tag{32}$$

where $\mathbf{A}$ – is the matrix that characterizes the dynamics of the system, $\mathbf{x}$ – is the state vector, $\mathbf{w}$ – is the input vector and $\mathbf{G}$ – matrix coefficients input vector;

$$\mathbf{x} = (\delta r^l \quad \delta v^l \quad e^l)^T, \tag{33}$$

$$\mathbf{w} = \begin{pmatrix} \delta f^v \\ \delta \omega_{iv}^v \end{pmatrix}, \tag{34}$$

$$\mathbf{A} = \begin{pmatrix} F_{rr} & F_{rv} & 0_{3\times3} \\ F_{rv} & F_{vv} & (f^l \times) \\ F_{er} & F_{ev} & -(\,\omega_{il}^l \times) \end{pmatrix} \tag{35}$$

and

$$\mathbf{G} = \begin{pmatrix} 0_{3\times3} & 0_{3\times3} \\ R_v^l & 0_{3\times3} \\ 0_{3\times3} & -R_v^l \end{pmatrix} \tag{36}$$

For the measurement equation

$$\mathbf{y} = \mathrm{H}\mathbf{x} + \mathbf{\nu}, \tag{37}$$

choosing the right components of the vector "y" following variables

$$\mathbf{y} = \begin{pmatrix} (\phi_{INS} - \phi_{GPS}) \cdot (R_m + h_{GPS}) \\ (\lambda_{INS} - \lambda_{GPS}) \cdot (R_n + h_{GPS}) \cdot \cos\phi_{GPS} \\ h_{INS} - h_{GPS} \end{pmatrix}, \tag{38}$$

resulting matrix H of the form

$$\mathrm{H} = \begin{pmatrix} R_m + h_{GPS} & 0 & 0 \\ 0 & (R_n + h_{GPS}) \cdot \cos\phi_{GPS} & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{39}$$

Therefore, by using the Kalman filter estimation errors desired positioning, speed and attitude INS using navigation solutions to this system and the GPS system and linearized model error of INS. Navigation solution provided by the integrated solutions offered by the correction of errors of the estimates of INS position, velocity and attitude (Fig. 1).

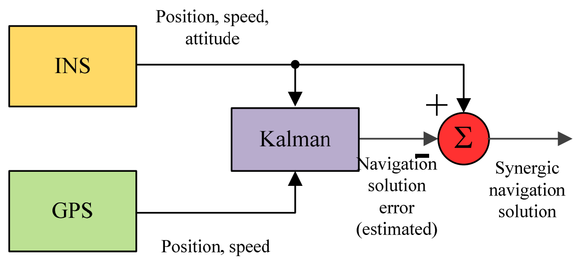

Fig. 1 INS/GPS synergy and Kalman filter

In discretized form, the equations of state are associated model error [14], [10], [15]

$$\mathbf{x}_{n+1} = \mathbf{F}_n \cdot \mathbf{x}_n + \mathbf{G}_n \cdot \mathbf{u}_n, \tag{40}$$

and

$$\mathbf{y}_n = \mathbf{H}_n \cdot \mathbf{x}_n, \tag{41}$$

where

$$\mathrm{F}_n = \mathrm{I} + \mathrm{A}(t_n) \cdot \Delta T, \tag{42}$$

$$\mathrm{G}_n = \mathrm{G}(t_n), \tag{43}$$

$$\mathrm{H}_n = \mathrm{H}(t_n). \tag{44}$$

Discrete noise covariance matrix resulting relationship process [15],

$$\mathrm{Q}_n = \mathrm{F}_n \cdot \mathrm{G}_n \cdot \mathrm{Q} \cdot \mathrm{G}_n^T \cdot \mathrm{F}_n^T \cdot \Delta T, \tag{45}$$

the covariance matrix of the process noise "Q" is expressed as [10], [14], [16], [17], [18]

$$\mathbf{Q} = \begin{pmatrix} \sigma_{ax}^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_{ay}^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_{az}^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_{\omega x}^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_{\omega y}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_{\omega z}^2 \end{pmatrix} \tag{46}$$

with $\sigma_{ax}^2, \sigma_{ay}^2, \sigma_{az}^2, \sigma_{\omega x}^2, \sigma_{\omega y}^2, \sigma_{\omega z}^2$ – standard deviations of accelerometers and gyro measurements.

After initializing the state vector $\bar{\mathbf{x}}_0$ and covariance matrix estimates $\bar{\mathrm{P}}_0$ status filtered amplification matrix iterative formula [16], [19], [20]

$$\mathrm{K}_n = \bar{\mathrm{P}}_n \mathrm{H}_n^T (\mathrm{R}_n + \mathrm{H}_n \bar{\mathrm{P}}_n \mathrm{H}_n^T)^{-1}; \tag{47}$$

R_n (3×3) the covariance matrix of measurement noise.

The next step in computing Kalman filtering algorithm is updating the measurements, which is achieved with formulas

$$\hat{\mathrm{x}}_n = \bar{\mathrm{x}}_n + \mathrm{K}_n (\mathrm{y}_n - \mathrm{H}_n \bar{\mathrm{x}}_n), \tag{48}$$

and

$$\hat{\mathrm{P}}_n = \bar{\mathrm{P}}_n - \mathrm{K}_n \mathrm{H}_n \bar{\mathrm{P}}_n, \tag{49}$$

at time n filter using the new measurement, y_n, to correct the condition $\bar{\mathrm{x}}_n$ to $\hat{\mathrm{x}}_n$ and to calculate the covariance matrix $\hat{\mathrm{P}}_n$ the estimates. In this respect, the filter is estimated to be the state at the time point $n + 1$ and its covariance calculated by the equations

$$\bar{\mathrm{x}}_{n+1} = \mathrm{F}_n \hat{\mathrm{x}}_n \tag{50}$$

and

$$\bar{\mathrm{P}}_{n+1} = \mathrm{F}_n \hat{\mathrm{P}}_n \mathrm{F}_n^T + \mathrm{Q}_n \,. \tag{51}$$

Integrated INS/GPS software implementation was performed using the software package Matlab/Simulink. The Kalman filtering algorithm was implemented in an embedded function called using a block interface.

The model has been tested experimentally acquired data simultaneously using the GPS module and the miniaturized inertial measurement unit, which consists of two accelerometric and gyro triads with MEMS sensors, both on board of a test vehicle. During the tests, the inertial system was not executed calibration procedures and compensating errors, the data being entered into the navigation algorithm in raw form. Data were acquired from the GPS system with a frequency of 5 Hz, while data from the inertial sensors are stored in a rate of 50 samples/s.

5. Experimental results

In this test, the values acquired from the IMU sensors are shown in Fig. 2. Although the test is a static, there is quite a large deviation from zero of the mean values for five of the six sensors (accelerometers for the axes *x* and *y* and the three gyro) and a significant deviation from the value of the acceleration to be measured local gravity ($-9.805\ \mathrm{m/s^2}$), indicated by the *z* – axis accelerometer. These significant values of bias will be reflected in visible navigation solution error provided by the inertial navigator. By numerical integration which is multiplied with time to determine speed and with square of time for determining the position of the square.

Using these signals with the solution provided by GPS system allows to obtain the errors of the estimated global positioning and speed very close to the direct differences between INS and the GPS solution. Evaluation of comparative graphics between them is shown in Fig. 3 for global positioning (latitude, longitude, altitude) and in Fig. 4 for the velocity components in local reference frame NED. Fig. 5 shows only the results for the estimates Kalman filter error of attitude, given that GPS navigation solution does not provide information on the vehicle attitude angles.

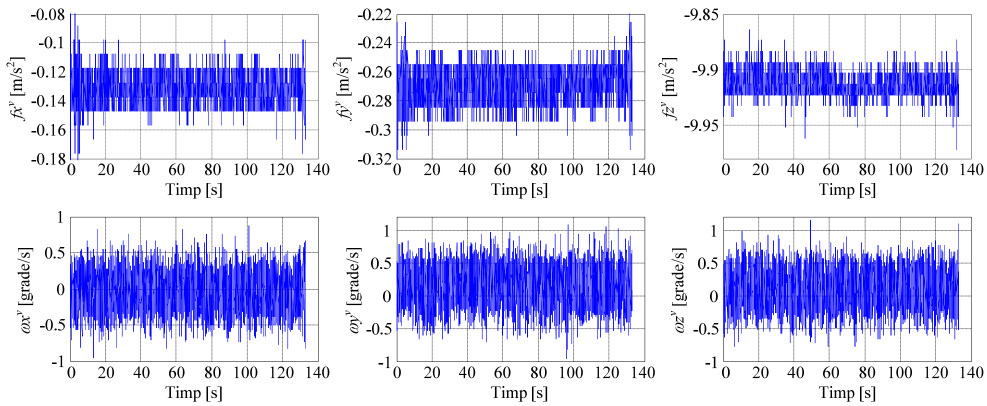

Fig. 2 IMU sensors data

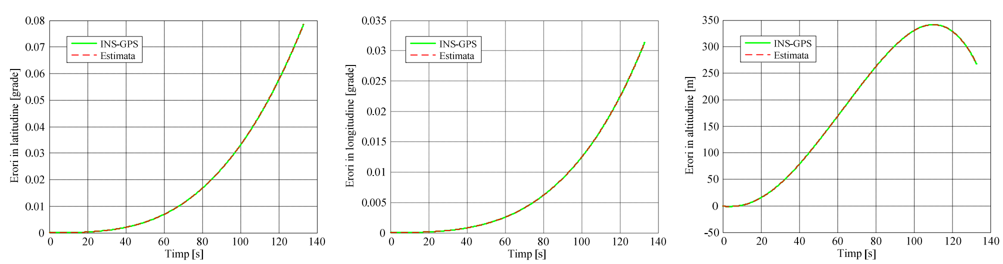

Fig. 3 Position errors in latitude, longitude and altitude

Kalman filter merging two independent navigators (INS and GPS) provided the maximum absolute values of the estimates of errors following values: 0.0786 degrees latitude, 0.0314 degrees longitude, altitude 341.32 m, 196.31 m / s for speed in a north direction, 60.97 m / s speed in an east direction, 7.52 m / s for speed in down direction, 3.63 degrees roll, pitch value of 11.08 degrees and 2.03 degrees yaw angle. As mentioned previously, no calibration procedures were performed and error compensation of sensors, signals are taken from them in raw form, which is seen from the high values of bias cleared their sites in accordance with Fig. 2. These large errors are due largely to bias sensors because in IMU architecture was use MEMS accelerometers and gyro which, because of miniaturization, are characterized by very low performance. Therefore, the high values obtained for the maximum absolute values of the estimates INS navigation solution are due to these errors uncompensated for the inertial sensors. The non-clearing procedures wanted evaluating Kalman filter performance in extreme conditions, these offsets cannot be done effectively.

Comparative analysis of the estimates provided by the Kalman filter error and those obtained by direct difference between the solution and the INS navigation GPS, revealed the following maximum absolute deviation between them: $1.7039 \cdot 10^{-5}$ degree latitude, $6.0894 \cdot 10^{-6}$ degrees longitude, altitude 0.30 m, 1.99 m / s for speed in a north direction 1.01 m / s for the speed of the East, 0.87 m / s for the speed of descent.

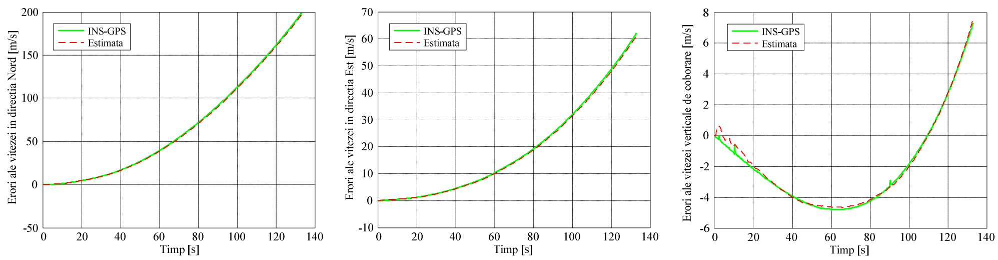

Fig. 4 Speed errors in Nord, East and Down direction

Graphic characteristics that describe the comparative three navigation solutions are given in Fig. 6 for global positioning (latitude, longitude and altitude) and velocity components in Fig. 7 referential NED. Fig. 8 shows the vehicle attitude angles (roll, pitch and yaw) after correction. Fig. 6 and Fig. 7 shows a very close between the solution obtained by correcting INS errors with the estimates provided by the Kalman filter and the solution provided by GPS. It is also noted the large differences between the two solutions and that provided by the INS, which is a consequence of the large errors affecting inertial sensors of the detection unit miniaturized inertial thereof.

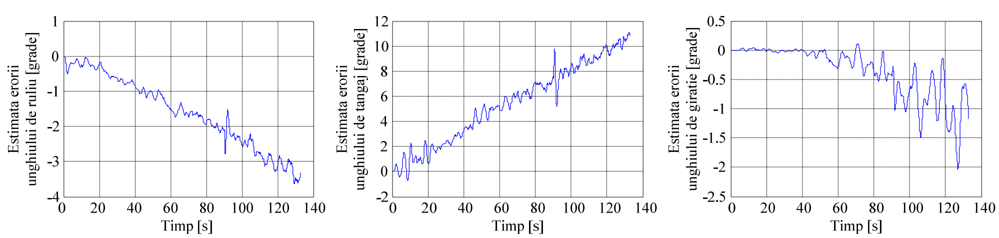

Fig. 5 Estimated attitude errors

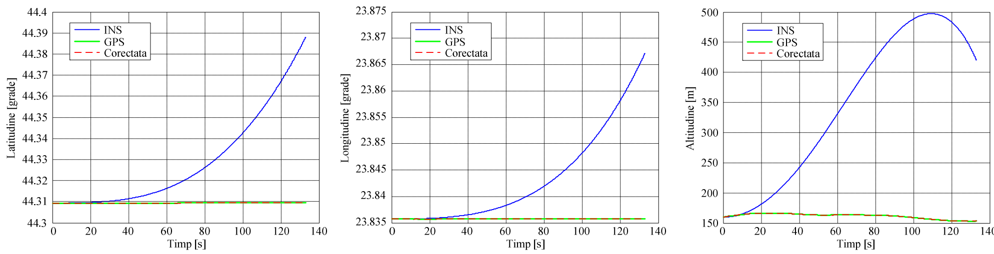

Fig. 6 Position components

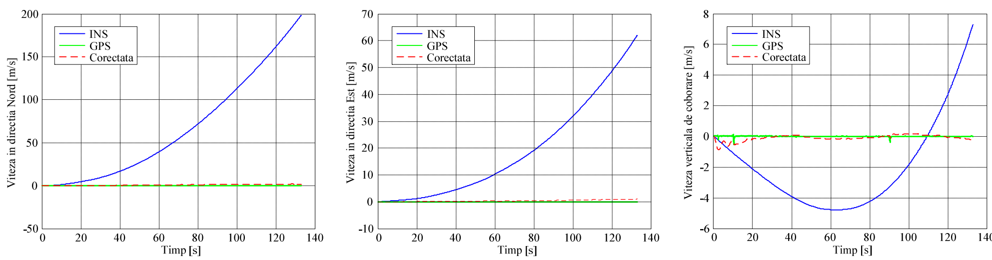

Fig. 7 Speed components in NED reference frame

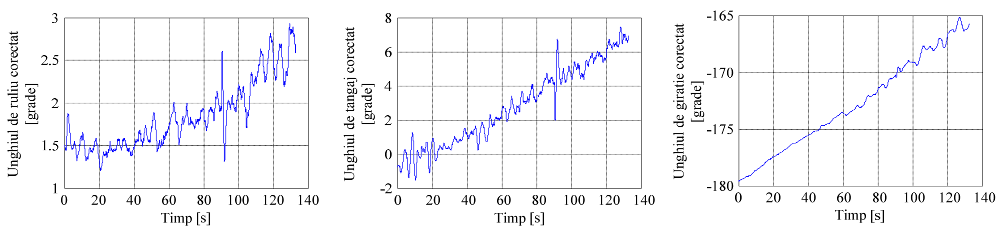

Fig. 8 Corrected attitude angle

6. Conclusions

This paper presented the development of a synergistic architecture INS / GPS based on a Kalman filter estimation that aims to estimate the positioning errors of INS velocity and attitude errors using navigation solutions to it, along with those provided by a GPS system.

To implement synergistic software INS / GPS has been used Matlab/ Simulink and embedded technology functions. The structure was tested experimentally, during the testing of inertial system was not performed calibration or compensation of inertial sensor errors.

The results obtained show a synergistic navigator INS / GPS with high precision, very good error correcting navigation solution induced inertial sensor errors. The test show a very close synergy between the solution obtained using the Kalman filter and the solution provided by GPS.

R E F E R E N C E S

[1] *N. Barbour and G. Schmidt*, "Inertial Sensor Technology Trends," IEEE Sensors Journal, vol. Vol. 1, no. No. 4, pp. 332-339., 2001.

[2] *G. Schmidt*, "INS/GPS Technology Trends," NATO RTO Lecture Series, RTO-EN-SET-116, Low-Cost Navigation Sensors and Integration Technology, Paris, 2010.

[3] *R. Collinson*, Introduction to avionics, Chapman & Hall, 1996.

[4] *J. Farrell and M. Barth*, The Global Positioning System and Inertial Navigation, New York: McGraw-Hill, 1999.

[5] *R. E. Hopkins, N. M. Barbour, D. E. Gustafson and P. Sherman*, "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, Paris, 2010.

[6] *D. H. Titterton and J. Weston*, Strapdown inertial navigation technology - 2nd Edition, Institution of Engineering and Technology, 2004.

[7] *O. Salychev*, Inertial Systems in Navigation and Geophysics, Moscow: Bauman MSTU Press, 1998.

[8] *R. Rogers*, "Applied Mathematics in Integrated Navigation Systems," AIAA, no. Third Edition, 2007.

[9] *T. L. Grigorie*, Sisteme de naviga□ie iner□ială strap-down. Studii de optimizare., Craiova: Editura Sitech, 2007.

[10] *E. Bekir*, Introduction to Modern Navigation Systems., World Scientific Publishing Co. Pte. Ltd., 2007.

[11] *I. Aron*, Aparate de bord pentru aeronave, Bucureşti: Editura Tehnică, 1984.

[12] *K. Britting*, Inertial Navigation Systems Analysis, New York: Wiley, 1971.

[13] *C. Broxmeyer*, Inertial navigation Systems, New York: McGraw-Hill, 1964.

[14] *D. Arden*, "MEMS/GPS Kalman Filter," Defence R&D Canada, Ottawa, 2007.

[15] *E. H. Shin*, "Accuracy improvement of low cost INS/GPS for land application," University of Calgary, Calgary, 2001.

[16] *M. S. Grewal*, *L. R. Weill and A. A. P.*, Global Positioning Systems, Inertial Navigation, and Integration, John Wiley and Sons, Inc., 2001.

[17] *S. Guerrier*, "Integration of Skew-Redundant MEMS-IMU with GPS for Improved Navigation Performance," Lausanne, June 2008.

[18] *V. Kumar*, "Integration of Inertial Navigation System and Global Positioning System using Kalman filter," Departament of Aerospace Engineering, Indian Institute of Technology, Bombay, 2004.

[19] *J. Farrell*, Aided Navigation. GPS with High Rate Sensor, McGraw-Hill, 2008.

[20] *G. Welch and G. Bishop*, "An Introduction to the Kalman Filter," University of North Carolina at Chapel Hill, Chapel Hill, 2006.