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STATIC INITIAL AZIMUTH UPDATE METHOD IN LAND NAVIGATION SYSTEMS

ABSTRACT. The paper presents a method for the ***initial azimuth*** Ψ_0 selection in *Land Navigation Systems* (**LNS**), applying the **ZUPT** (***Zero–velocity UPdaTe***) technique. This technique is understood as a correction of the *initial setting* Ψ_0 achieve the best accuracy of the navigation. The case of the *inaccurate initial azimuth* during *stopping of the vehicle* (after short drive) in order to setting is considered. The first part of the work describes the ***Static Initial Azimuth uPdate*** (**SIAP**) method. Next, the *vehicle stopping criteria* and their influence on the *accuracy of the navigation* are discussed. Then, the *initial azimuth optimization* method is proposed. Finally, the simulation results and conclusions concerning further research are presented.

INTRODUCTION

The ***initial settings*** selection of *alignment angles*: Θ_0 - *pitch*, Φ_0 - *roll* and Ψ_0 - *heading* (***initial azimuth***) has an essential influence on the *Land Navigation Systems* (**LNS**) correct operation. Depending on the *self-Alignment Process* (**AP**) time and *mechanical disturbances* occurrence (vibrations or accelerations), we can distinguish several possibilities of the ***initial settings*** selection. This is illustrated in Fig.1.

In further considerations we focus our attention on the cases in which we assume the *inaccurate initial azimuth* Ψ_0 setting (these cases are outlined by the dashed line in Fig.1).

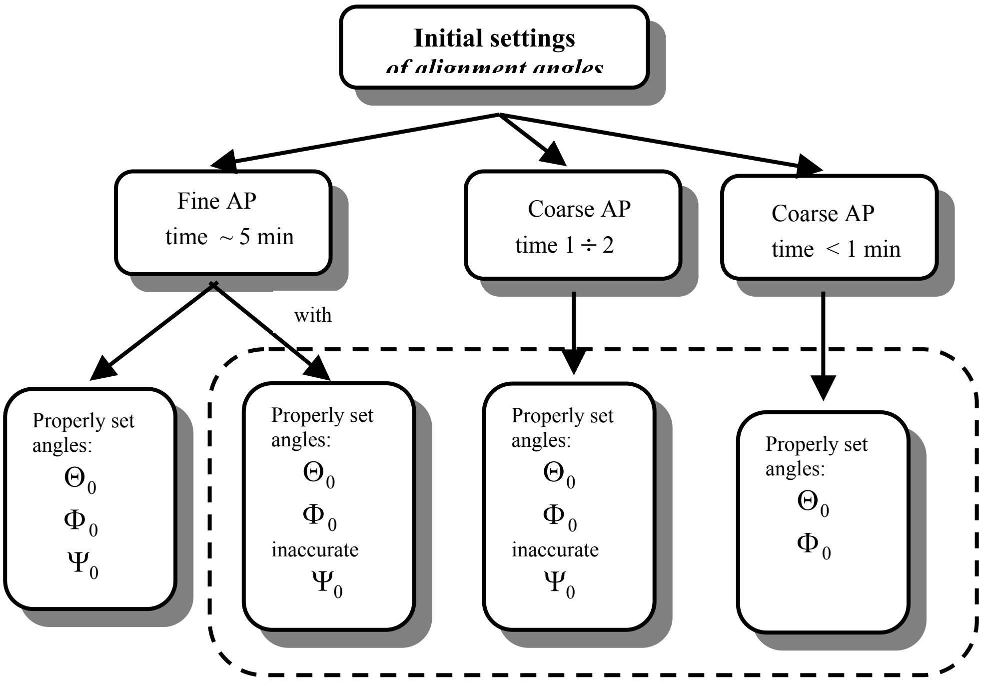


Fig.1. AP *initial settings* selection

The logging *raw data* from **PIT UNZ-50** system (Fig. 2) – containing **LITTON IMU LN-200** with triad of **FOG** gyros of l deg/h bias and triad of silicon accelerometers of 1 mg bias - have been used for simulation and optimization. We assume a possibility to collect these data in real time.

Fig.2. UNZ-50 System

METHOD PRESENTATION

Let us assume that a vehicle equipped with an inertial navigation system is located at the *latitude* φ in the *heading* $\Psi = 0$. *Pitch* and *roll* angles equal $\Theta = \Phi = 0$ and the **AP** is taking place. As a result, ***initial settings*** angles are defined. *Initial pitch* and *roll* angles equal $\Theta = \Phi = 0$ while the *heading* has been defined as $\Psi = \delta$. The angle δ is an ***initial heading error.*** Its value depends upon the *gyroscope drift*, as follows

$$\delta = \frac{B}{\Omega_z * \cos\varphi} = \frac{B}{\Omega_{ZH}} \tag{1}$$

where: $B = B_x = B_y$ are gyroscope drifts in the X and the Y axes

Ω_z - Earth angular rate

φ - latitude

Ω_{ZH} - Earth angular rate horizontal component

Moreover, an *initial heading error* can be caused by *outside disturbances* occurring during *alignment process* (i.e., a strong wind or a working engine etc.) as well as too short period of **AP** time.

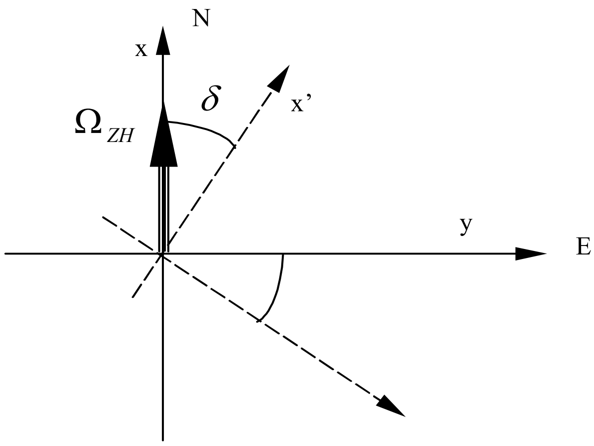
When the **AP** is over, the system enters into a *navigation mode*. We assume an ideal *navigation process*, namely, the only errors that occur, result from an *inaccurate initial azimuth* setting. Further, we assume that, after a defined period of time T, the vehicle returns to the former position. Once it is stopped, the *vehicle stopping criteria* are verified, and *pitch* and *roll* angles are measured. To simplify the analysis, we can assume that in the *navigation* mode, the vehicle is not in motion, it does not change its location. This case is illustrated in Fig. 3.

Note that the x-axis is directed exactly to the North, while the x' axis represents an actually measured direction burdened with the error. In a normal terrestrial system, the ***earth rotation rate components*** are:

$$\begin{aligned} \Omega_x &= \Omega_z \cos\varphi \\ \Omega_y &= 0 \end{aligned} \tag{2}$$

However, they are measured in the y' x' frame, thus:

$$\begin{aligned} \Omega_{x'} &= \Omega_z \cos\varphi \cos\delta \\ \Omega_{y'} &= \Omega_z \cos\varphi \sin\delta \end{aligned} \tag{3}$$



Rate variances in the corresponding axes (2) and (3) produce *pitch* and *roll* error increase. The corresponding *angular rate error values* in both axes are:

$$\begin{aligned} \mathbf{p}' &= \Omega_z \cos\varphi (1-\cos\delta) \\ \mathbf{q}' &= \Omega_z \cos\varphi \sin\delta \end{aligned} \tag{4}$$

In accordance with *cinematic equations*, these rates can be related to *pitch* and *roll* angle changes.

$$\begin{aligned} \dot{\Theta}' &= \mathbf{q}' \cos\Phi \\ \dot{\Phi}' &= \mathbf{p}' + \mathbf{q}' \sin\Phi \operatorname{tg}\Theta \end{aligned} \tag{5}$$

Above equations disregard elements containing the **r’** component (the rate variance in the z’ axis). We assume that, if a *vehicle position* is known, then this component can be defined and totally *compensated*. With the adopted introductory assumption that: $\Theta = \Phi = 0$, and as a result of these (angles value error growing), they will remain at a minor level (i.e., below 1 deg), these equations can be formulated:

$$\begin{aligned} \dot{\Theta}' &= \mathbf{q}' \cos\Phi \approx \mathbf{q}' = \Omega_z \cos\varphi \sin\delta \\ \dot{\Phi}' &= \mathbf{p}' + \mathbf{q}' \sin\Phi \operatorname{tg}\Theta \approx \mathbf{p}' = \Omega_z \cos\varphi (1-\cos\delta) \end{aligned} \tag{6}$$

For the *North latitude* of 52 deg, *angular rate error values* in both axes with respect to the *initial heading error* for the whole range of changes are illustrated in Fig 4.

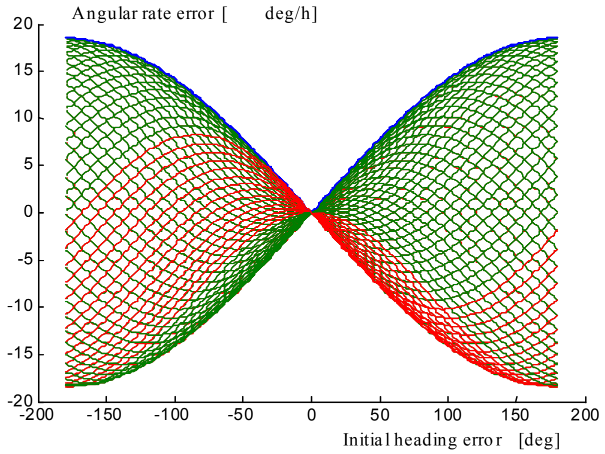


Fig.4. The *angular rate error* in the both axes with respect to the *initial heading error*

Geometric sum of velocities $\dot{\Theta}'$ and $\dot{\Phi}'$ has been adopted as a *criterion of inclination* from a vertical:

$$\mathbf{W} = \sqrt{\dot{\Theta}'^2 + \dot{\Phi}'^2} \tag{7}$$

The w *criterion* with respect to the *initial heading error* is illustrated in Fig. 5, as an upper envelope of diagrams family. As it is shown, the change of this criterion depends solely on an *initial heading error*, and it does not depend on the current *heading* value. Thus, it could serve to evaluate *an initial heading error*, disregarding the *heading* changes that might occur during the navigation process.

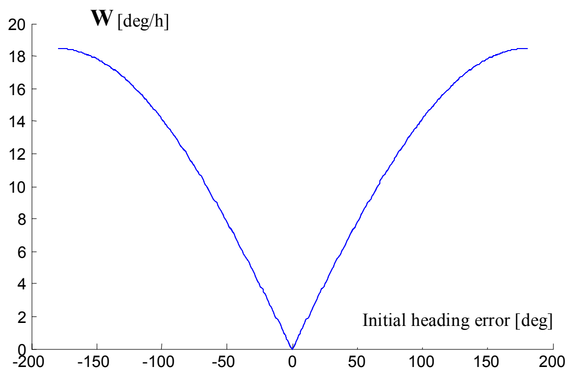


Fig.5. The w *criterion* with respect to the *initial heading error*

Following the *navigation time* ***T***, the criterion (7) can be rewritten as:

$$U = \mathbf{W}T \tag{8}$$

Let us notice, that w (7) as well as *U* (8) *criteria* have a *unique minimum* in respect to the *initial heading error*, thus to find this value we can apply any ***optimization algorithm***.

Static Initial Azimuth uPdate (SIAP) method:

1. after **AP** (with an error δ), start the *navigation process* - the vehicle is in motion during T minutes and moves with a defined speed v_P
2. stop the vehicle and record the angles basing on *gyros output data*: Θ_N, Φ_N
3. verify if the *vehicle stopping criteria* are fulfilled. If so, record the angles basing on *accelerometers output data*: Θ_P, Φ_P
4. calculate *pitch* and *roll* angle errors

$$\begin{aligned} \Delta\Theta &= \Theta_N - \Theta_P \\ \Delta\Phi &= \Phi_N - \Phi_P \end{aligned} \tag{9}$$

and the value of the *U* (8) *criterion*

$$U = \sqrt{\Delta\Theta^2 + \Delta\Phi^2} \tag{10}$$

5. find an optimal value of the initial azimuth **azpopt** which minimizes the criterion (10)

Let us note that in this method we can distinguish two important points influencing the *accuracy* of *calculations* of the *optimal value* ***azpopt***, namely:

- adopted *vehicle stopping criteria*
- applied *minimization procedure*

In order to consider these issues, Chapter 3 presents adopted *vehicle stopping criteria* and examines their influence on the **SIAP** algorithm, while Chapter 4 describes the method and *initial azimuth* optimization results.

VEHICLE STOPPING CRITERIA

The basic *criteria* - serving to determine whether a vehicle is in motion or whether it is *stopped* – adopted in [3] and [4], make use of the following measurements:

1. the low-pass filtered averaged angular rate
2. the low-pass filtered averaged linear acceleration

The first one is applied to verify whether existing outer conditions (disturbances) allow for execution of an *alignment algorithm*. This criterion has been formulated, as follows:

$$Kryt1 = \Omega_z - \sqrt{onx^2 + ony^2 + onz^2} \tag{11}$$

where *onx*, *ony*, *onz* are low-pass filtered averaged angular rate components

If $|Kryt1| \le EPSGM$, then the *vehicle stop* is recognized as the ***stop***, and the **AP** can be initiated.

As it has been shown in [4] and [5], the *EPSGM* selection has a great influence on the **SNL** correct functioning. Furthermore, it is important to select properly the *low-pass filter* to filter out disturbances.

The ***second criterion*** is formulated below:

$$Kryt2 = gz - \sqrt{afx^2 + afy^2 + afz^2} \tag{12}$$

where:

gz is gravitational acceleration

afx, *afy*, *afz* are low-pass filtered averaged linear acceleration components

If $|Kryt2| \le EPS$, then the *vehicle stop* is recognized as the ***stop***, and the **AP** can be initiated. Also, both criteria combinations can be applied.

In order to examine the influence of both criteria on the **SIAP** method, a series of simulations in MATLAB 6.0 environment have been carried out on the *data* collected during *terrain tests* of **UNZ-50** system prototype mounted on a cross - country light vehicle. Fig.6 and Fig.7 illustrate the examples of simulation results.

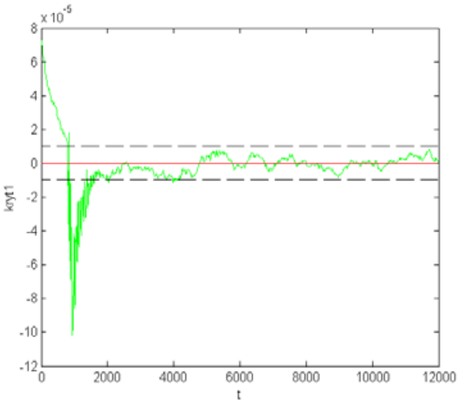


Fig. 6. *Kryt*1 with respect to *t* - *dashed lines* define the *interval* in which the *criterion is fulfilled*: $|Kryt1| \le EPSGM$

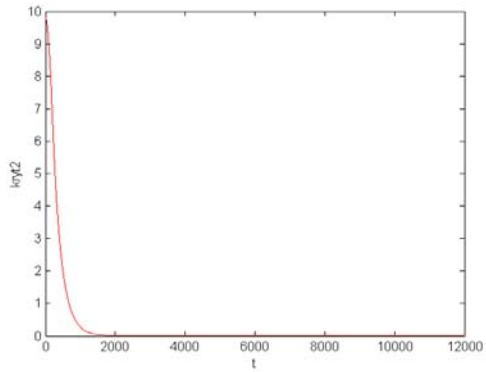


Fig. 7. *Kryt*2 with respect to *t*

Analyzing these simulation results, let us note:

1. *Kryt*2 has a *monotonic*, *undisturbed* character, thus for any $EPS \ge EPSMIN$, the *moment* of measurements Θ_P and Φ_P can be exactly defined. The value of *EPSMIN* determines the *bound* below which influence of *EPS* on *Kryt*2 is very small
2. *Kryt*1 has an *oscillating*, *disturbed* character, thus additionally the initial delay T_0 must be defined, after which this criterion can be applied and the *moment* of measurements Θ_P and Φ_P can be properly defined.

INITIAL AZIMUTH OPTIMIZATION

As it has been described in step (5) of the **SIAP** method, an *optimal value* of the *initial azimuth* ***azpopt*** can be found using an *optimization algorithm*, which minimizes the *criterion* (10).

The ***initial azimuth optimization problem*** can be formulated as follows:

$$\min_{azp \in X} \left\{ U(azp) = \sqrt{\Delta\Theta^2(azp) + \Delta\Phi^2(azp)} \right\} \tag{13}$$

where: ***X*** is the *feasible solutions set*, defined below:

$$X = \{azp : azpD \le azp \le azpG\} \tag{14}$$

where: azpD is a lower bound, and azpG – upper bound

To solve the problem (13), the *optimization algorithm* called ***fminbnd*** [1] has been used, in accordance with the diagram presented in Fig. 8.

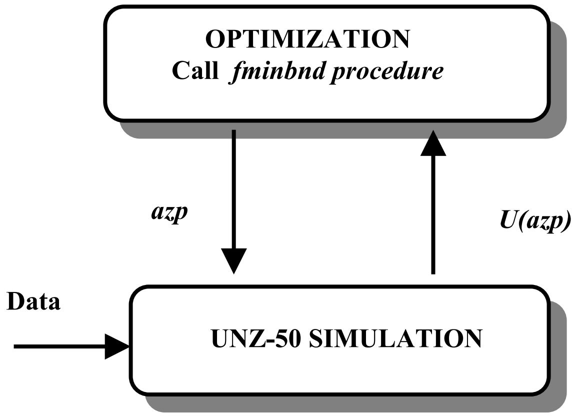


Fig. 8. Initial azimuth optimization diagram

In order to check proper functioning of the **SIAP** method, a series of simulations in MATLAB 6.0 environment have been carried out on the *data* collected during *terrain tests* of **UNZ-50** system prototype mounted on a cross - country light vehicle. The ***optimization results*** for the selected data sets – called *F1.dat*, *F2.dat* – are presented in **Table 1**, while the ***U*** *criterion* with respect to the *initial azimuth* ***azp*** (for the *F2.dat* file) is illustrated in Fig. 9.

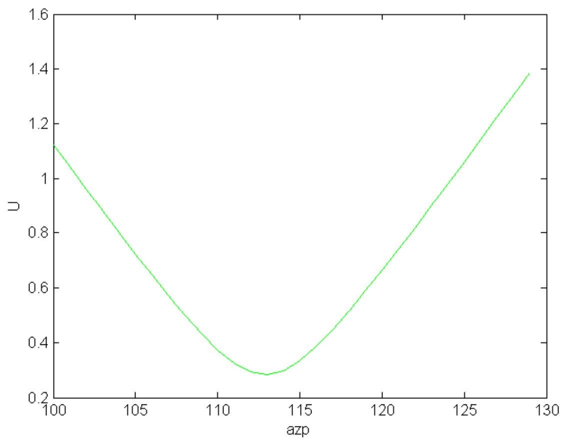


Fig. 9. The *U criterion* with respect to *azp*

Table 1. Optimization results

No	*File name*	*psir Reference*	*azp Initial*	*azpopt Optimal*	*Simulation*		*Error*	
					psit *Typical*	***psio*** *Optimal*	*psir-psit*	*psir-psio*
1.	*F1.dat*	72.562	108.714	107.02 00	73.864	72.172	1.302	0.39
2.	*F2.dat*	92.689	109.503	112.8875	86.127	89.494	6.592	3.195

CONCLUSION

The study contains an analysis of the ***Static Initial Azimuth uPdate*** (**SIAP**) method by the ZUPT technique described in [4] and [5]. This method disregards ***traditional initial setting*** *(self-alignment)* lasting generally about 5 ÷10 min. It has been replaced with *short levelling* (about 1 min), in order to identify the angles: Θ_0 and Φ_0 and the system passes into the *navigation* mode. After about 15 ÷ 25 min of driving and a second *short levelling*, an *initial azimuth*, as a result of the ***U*** *criterion* (10) optimization, can be recreated. Obtained *simulation results* show considerable improvement of the *initial azimuth accuracy* and consequently a correction of the *coordinates of current position*.

It seems that above discussed method could be widely applicable provided that:

1. The *minimum time* and *minimum speed* of the first drive are properly defined. On one hand, the time should be *as brief as possible* in order to reduce the number of calculations for finding *minimum values,* on the other – *long enough,* so that the measurements taken at the final moment are sufficiently accurate.
2. The *vehicle is stopped* in such a manner that whichever *vehicle stopping criteria* are fulfilled.
3. The proper optimization method has to be applied to find the *optimum value* of the *initial azimuth*. The present study has been based on the *optimization method* contained in the MATLAB 6.0 Optimization Toolbox [1] library. In the case of a system operating in the *real time*, the *new effective optimization method*, compatible with **UNZ-50** system software, has to be implemented.
4. The *first drive section* (15 ÷ 25 min) goes along a *smooth surface*.

Note that the **SIAP** method offers particular advantages in the case of a lack of *azimuth external sources* (i.e., GPS).

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