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PARTICLE FILTERING TECHNIQUE FOR AIRCRAFT CONTROL IN HIGHLY-DISTURBED GPS-DENIED ENVIRONMENT

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Abstract**—***The problem of aircraft control is considered for certain class of situation, namely when aircraft enters GPS-denied zone with significant disturbances of different nature which may cause the constructive damage and the loss of control. The only source of information is from inertial navigation system that need to be aided by correlation extreme navigation system, for example. In the paper the control problem is solved by using particle filtering technique for correlation extreme navigation system which outputs form the control vector. Further the structural reconfiguration is done by redistributing control or changing the control law in order to create the necessary control forces and moments, maintain acceptable control quality and return for the desired track. The lack of reliable navigation information is compensated by correlation extreme navigation system working by terrain filed of the Earth to be included into control contour. The researches have been conducted by mathematical modeling of the developed algorithms in mathematical software package MATLAB using terrain field (the part of Carpathians territory). The results proved the high accuracy of navigation solution and stability of control estimated by error of closing loop.*

Index Terms—Correlation extreme navigation system; particle filtering; relief field; control uncertainty; control reconfiguration.

I. INTRODUCTION

Aircraft performance characteristics undergo significant changes during the long-term operation. More significant aerodynamic changes occur while the sudden damage of external contour of the aircraft due to collision with its surface at high speeds, mechanical, biological, electrical or other foreign objects. The danger of such damages is that they are random in nature and their occurrence can not be foreseen. The result of these collisions, depending on the speed and mass of the object can be as minor dents, and the catastrophic destruction of the aircraft structure or its systems. Unfortunately, existing methods of monitoring and diagnosis [3], [10] does not allow to register changes of the external contour of the aircraft itself in flight. At the same time, the availability of complete and accurate navigation information about the actual aircraft position and velocity allows us to objectively evaluate the development of an emergency situation and take necessary action to prevent its development by reorganizing the aircraft flight control or change the aircraft flight mode.

The main source of navigation information is satellite radio navigation systems like Global Positioning System (GPS). But it has the disadvantage of relying on information broadcasted to the aircraft. This information could be deliberately jammed in a hostile situation, or the transmitters could be destroyed, leaving the aircraft without navigation support, or the reception can be complicated, for example, in polar regions. Thus, GPS provides the position and velocity information with high accuracy used for correction of inertial navigation system (INS) and for controlling the aircraft, but still it has to be complemented with alternative backup systems using other navigation principles.

Such alternative system can be correlation extreme navigation system (CENS). It is the system of processing of information, which is represented as random functions (geophysical fields). Correlation between realizations of random functions and reference map is the basic feature. The determination of coordinates is done by finding the extreme point of correlation function of current measurements with reference map [7].

Geophysical fields are divided depending on their physical origins (magnetic, relief, gravitational, etc) and on the level of informativity. Here and further in consideration the relief field will be used. It is characterized by the mutual arrangement of heights, that is, the changes (elevations) in the terrain relative to a certain level, for example, mean sea level (MSL). To measure the field parameters on board of the aircraft the radio altimeters or range finders together with barometric altimeters and INS are used. The aircraft altitude over MSL is measured with the barometric altimeter and the ground clearance is measured with a radar altimeter, pointing downward. The terrain elevation beneath the aircraft is found by taking the difference between the altitude and ground clearance measurements. The navigation computer holds a digital reference map with values of the terrain elevation as a function of longitude and latitude. The measured terrain elevation is compared with this reference map and matching positions in the map are determined.

The relief (terrain) field of the earth's surface is a natural geophysical field that is considered to be one of the most stable in time (small influence from human activity on it). One more advantage is availability of good databases for this field with good resolution (1 arc-second~30 meters at equator). Today, the main way of representing the shape of the earth's surface is the digital model of the relief (DEM), a regular grid of heights, which can be obtained by space surveying using high-tech methods for remote sensing data processing. To create such products, stereopair images or interferometric pair (radar data only) are required to obtain information on terrain, as well as specialized software for further processing of the information.

To obtain current data of the relief field (elevations), an information on the difference between the absolute altitude and above MSL (measured by barometric altimeters) and the true altitude above the earth's surface (measured either by a radio altimeter or by laser / ultrasonic / infrared rangefinders) is used. It is clear that the displays of absolute height will change with the corresponding change in atmospheric pressure. Therefore, for the correlation analysis of the current implementation of the relief heights gradient is used more often instead of the height itself.

Thus, terrain based navigation uses information of the variations of the terrain to bound the errors of inertial navigation system. It is a self-contained technique, in the sense that no external aiding signals or devices are needed. It’s worth mentioning that this field was the first one used in correlation-extreme navigation systems, like TERCOM for example [11]. However, its drawback is that for some areas it has much less informative content in comparison with above mentioned fields.

II. PROBLEM STATEMENT

As reconfiguration we will understand the control redistribution on controls for the purpose of creation of necessary control forces and moments for restoration of airplane controllability and stability of aircraft in flight. Implementation of reconfiguration is possible for the airplanes with redundant controls. So, in [1] it is marked that for high-maneuverable airplanes with the decreased static stability, quitting on critical values of attack angle, for successful reconfiguration in case of failures eight independent governing bodies are necessary at least. The modern and perspective high-maneuverable airplanes possess a large number of controls: elevons (section with independent control of each section), front horizontal empennage, spoilers, rudders, turning nozzles, etc.

In the airplanes developed earlier, there are no means of automatic implementation of reconfiguration, these functions are completely laid to the pilot. Therefore the result of reconfiguration completely depends on experience and ability of the pilot though essentially reconfiguration would allow to prevent 70% of cases of incidents due to failures of actuators and controls (this inference is made in [8] based on the analysis of the flight incidents which were taking place in the USA).

In paper [1] two examples of successful and unsuccessful implementation are given by the pilot of reconfiguration. In the first case the left section of the elevator of the Delta L1011 airplane appeared is clamped in situation 19° in case of take-off. The pilot prevents failure by reconfiguration. The second case is connected to DC-10 airplane failure on May 25 1979 in Chicago, called loss of section of the flap of the airplane. The subsequent simulation of a situation showed that the pilot could avoid failure by means of reconfiguration.

In this regard it is expedient to put at a development stage of AFCS of airplanes in system of means of automatic implementation of reconfiguration. In this direction in 1994 the U.S. Air Force laboratory of flight dynamics began development of the SRFCS program (Self-Repairing Flight Control System) [2] which purpose is implementation by development of AFCS of the modern and perspective airplanes of the actions providing reconfiguration and diagnosing of system and directed finally on reliability augmentation, fail safeties, survivability. The SRFCS program provides two basic approaches [2]. The first is connected to the automatic reconfiguration, the second with creation of the expert diagnostic systems making recommendations to the pilot depending on the developed flight situation.

Development of methods and models of reconfiguration of controlling influences aboard the plane in the conditions of origin special situations in flight operation [4] is devoted. For reconfiguration of controlling influences in case of failures of drives and governing bodies two approaches [4] are used: parametric and structural.

The basics of proposed CENS (Fig. 1) is given in [6] and its reduced version includes the following elements: sensor (s) of the geophysical field; correlator; automatic optimizer; map-based referencing block; inertial navigation system (INS) or other navigation system to be corrected; data fusion block.

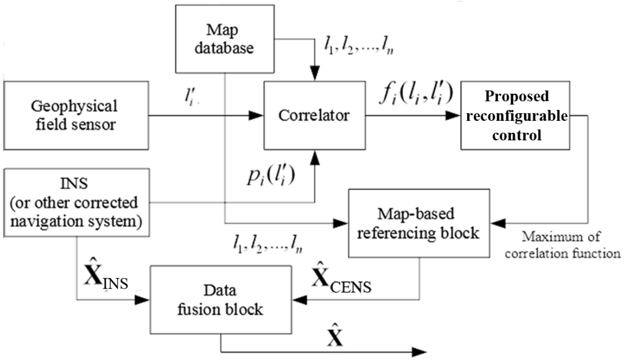

Fig. 1. Generalized Block-Scheme of Correlation-Extreme Navigation System

The geophysical field sensor outputs information in the form of the current field realization l'_i, which is represented as discrete point data, extended linear or in the form of a frame, depending on the type of anomalous geophysical field.

For the first measurement option, the field parameter is taken in the form of a scalar value at each time point; both types of fields can be used, surface and spatial. For the second sensing option, the sensor measures field parameters along an arbitrarily selected line instantaneously or over a short period of time. For the third option, the field parameters are measured from some part of the earth's surface during a short scan cycle ("frame").

The cartographic unit contains information about the reference (template) implementations of the field $l_1, l_2, \ldots, l_n$, which are presented as a regular or irregular grid, in the form of an isoline or as an analytical model.

The correlator performs the calculation of the value of the correlation function $f_i(l_i, l'_i)$ for each template stored in memory, or, if there is a priori knowledge of the flight route, the calculation of the correlation function for only one template.

In the latter case, the presence of the automatic optimizer is optional, since there is no need to look for the extremum (maximum) of the correlation functions of the pairs of reference and current field implementations.

The INS provides a priori information about the current location of an object. Taking into account the INS errors on the input of the correlator, the a priori probability of the location of the object arrives in the form of the probability of coincidence of the current implementation of the field with some template $p_i(l'_i)$. Also, INS provides the estimate of state vector $\hat{\mathbf{X}}_{\text{INS}}$ into data fusion block, where it is corrected using the previous navigation information from CENS $\hat{\mathbf{X}}_{\text{CENS}}$ (map-based referencing block).

The hypothesis about the possible location of a moving object is checked according to information from the INS. The reliability of each hypothesis is determined by the value of the functional as a measure of proximity (similarity) between the on-board measurement of the field and the realization of the field obtained from the memory of the cartographic unit. In the presence of significant inaccuracies in cartographic information, the risk of making a false hypothesis increases.

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In operational practice there may be some deviation of the quality of the systems operation of the aircraft which do not lead to the loss of their ability to work, i.e. permissible changes occur in a whole aircraft state. These deviations assign change the aerodynamic conditions of the external contours of the aircraft in flight. Permissible changes in the state of the external contours of the aircraft form a subset of states $\{N_i\}$, in which the aircraft is operational. In the future change of aerodynamic and technical condition of the aircraft shall be regarded as a change in the degree of disability or the stock of aircraft performance. In addition, if these changes do not exceed prescribed limits, $N_i \in N_0$, where N_0 is the stock performance object. If the change in the degree of disability beyond the permissible $N_i \notin N_0$, then the object loses its efficiency, i.e. brings a state of failure. It is obvious that the stock performance of the object is determined by the conditions under which the $\{N_i\}$ does not go beyond N_0.

Aerodynamic surface of the aircraft will submit the three main components: the carrier surface (aerodynamic wing surface), the fuselage (the aerodynamic surface of the fuselage), tail surfaces (aerodynamic surface of the tail).

Let us consider the damage in wing to difficult the control of aircraft. Wing is the basic element that creates lift aircraft. But with the lifting force of the wing is always a source of resistance and the longitudinal moment.

Evaluation of changes to the aerodynamic conditions of an airplane wing in flight provides the definition of storage conditions, stock performance, the choice set of variables, allowing to check the status of an airplane wing in flight, the identification of methods for measuring and monitoring these values and the search for methods of determining the extent and time of occurrence of an injury. It is known that any damage to the external contour of the aircraft leads to the instantaneous change in the aerodynamic forces and moments acting on it. Therefore, to monitor in-flight condition of the aircraft aerodynamic surface and determine its damage, which occurred suddenly need a check number, in general, interrelated parameters that characterize these changes.

For control the aerodynamic surfaces condition of aircraft in-flight of and determine the place of injury is needed testing a number of generally interdependent parameters:

$$\mathbf{Z}_0 = [n_x, n_{x0}, n_y, n_{y0}, n_z, n_{z0}, \omega_x, \omega_{x0}, \omega_y, \omega_{y0}, \omega_z, \omega_{z0}]^T,$$

nominal value of each of which is ensured by a certain subset Ω_i. Each parameter is evaluated by testing the reaction in pre-selected points on the surfaces of a mechanical or electro-dynamic forcing. We denote a test that checks the status of a subset of surfaces Ω_i, $i = 1, m$. As a result of each test can only be two outcomes: "no damage" if

$$\begin{cases} \hat{\mathbf{e}}(k/k) = \mathbf{Z}(k) - \hat{\mathbf{Z}}(k) = 0, \\ \tilde{\mathbf{e}}(k/k) = \mathbf{Z}(k) - \tilde{\mathbf{Z}}(k) = 0, \end{cases} \qquad (1)$$

where $\mathbf{e}(k/k)$ is the discrepancy, which appear due to violation of an aerodynamic surface $\hat{\mathbf{Z}}(k)$ is estimate $\mathbf{Z}(k)$ which includes measurements on the k th step, $\tilde{\mathbf{Z}}(k)$ is estimate to measure on k th step – "damage", if appeared damagedat least one point belonging to the aerodynamic surface Ω_i:

$$\begin{cases} \hat{\mathbf{e}}(k/k) = \mathbf{Z}(k) - \hat{\mathbf{Z}}(k) \neq 0, \\ \tilde{\mathbf{e}}(k/k) = \mathbf{Z}(k) - \tilde{\mathbf{Z}}(k) = 0. \end{cases} \qquad (2)$$

Estimate vector $\hat{\mathbf{Z}}(k)$, the satisfying requirements (1) and (2) is the conditional mean

$$\hat{\mathbf{Z}}(k/k) = M\left\{\mathbf{Z}(k)/\mathbf{Y}_1^k\right\}. \qquad (3)$$

Changes in the aerodynamic forces and moments acting on aircraft in flight, are due to changes in local aerodynamic forces and moments of change in their coefficients. Dimensionless aerodynamic coefficients of forces and moments in the case of sudden damage to the external contours of the aircraft is a function not only of angles of attack and slip, the Mach number, altitude, alignment, proximity to land, deviations of control and configuration of the aircraft, but also the functions of the damage location and nature.

III. SOLUTION OF THE PROBLEM

Estimation of state vector is done using novel approach of probabilistic filtering namely particle filter [11] and extra estimation of measurement vector for diagnostics of possible wing damages is done by proposed approach of control reconfiguration [5].

Therefore, in further consideration, such CENS model and mathematical apparatus must be used for data fusion of navigation information, which are minimally sensitive to the following limiting factors:

1) multimodal distribution of the probability of matching between of the reference and the current realizations of the field;

2) the significant nonlinearity of the measurement equation for CENS, in particular, the correspondence between the measured values of geophysical field and the current coordinates is presented as map database, and in most cases cannot be analytically approximated;

3) the initial uncertainty of the current coordinates due to the INS errors increase in time and significantly affect the area of initial search, and accordingly influence the time efficiency and accuracy of the navigation solution.

Obviously, for the evaluation of in-flight changes in the aerodynamic state of the external contour of the aircraft, including in instances of sudden damage to the external contours, it is necessary to expand the state vector $\mathbf{X}$ for the cases that are investigated:

$$\dot{\mathbf{X}} = (\mathbf{A} + \mathbf{BK})\mathbf{X} + \mathbf{HZ}, \tag{4}$$

where **A**, **B**, **H** are corresponding to the matrices of arguments, **K** is the matrix, which is positive solution of the algebraic matrix Riccati equation.

The expression (4) shows that the relevant forces and moments get a big change, the more damage inflicted by the external contour of the aircraft in flight. In addition, it is clear that for the aerodynamic moments is of great importance not only to the nature of damage, but also a place of its occurrence.

Thus, extending the state vector to its values at (4), we can take into account the effect of mechanical damage to the external contours of the aircraft in flight. However, for diagnosing the state of aerodynamic aircraft in flight, it is necessary that the extended state vector (4) was fully observed, that is the minimum dimension of the vector:

$$\mathbf{Y} = (\mathbf{C} + \mathbf{BK})\mathbf{X}, \tag{5}$$

where **C**, **B** is the matrix of the coefficients, which provides full observability of the aerodynamic state of the aircraft.

For particle filtering let us suppose that statistic properties of process and measurement noises are supposed to be known, and the noises are considered as white and independent.

The particle filter with fixed grid is based on the statistical methods (Monte–Carlo method) with grid state-space approximation. The state vector is defined along the finite grid of discrete values (points). There is a deterministic grid $\left\{\mathbf{x}_k^{(i)}\right\}_{i=1}^{N}$ of the state space over N number of points (particles). The posterior distribution density from (4) is approximated by the sum:

$$p(\mathbf{x}_k \mid \mathbf{Z}_k) \approx \sum_{i=1}^{N} \overline{w}_k^{(i)} \delta_{\mathbf{x}_k^{(i)}}\left(\mathbf{x}_k\right), \tag{6}$$

where $\delta_{\mathbf{x}_k^{(i)}}\left(\mathbf{x}_k\right)$ denotes the Dirac impulse function, and the weighting coefficient $\overline{w}_k^{(i)}$ corresponds to the probability that $\mathbf{x}_k^{(i)}$ will have the value close to the true one.

Operation of particle filter is based on Bayes theorem and uses the posterior distribution determination by likelihood function:

$$p\left(\mathbf{X}_{k+1}^{(i)} \mid \mathbf{Z}_k\right) = \underbrace{p\left(\mathbf{x}_{k+1}^{(i)} \mid \mathbf{X}_k^{(i)}, \mathbf{Z}_k\right)}_{p\left(\mathbf{x}_{k+1}^{(i)} \mid \mathbf{x}_k^{(i)}\right)} \underbrace{p\left(\mathbf{X}_k^{(i)} \mid \mathbf{Z}_k\right)}_{w_{k|k}^{(i)}} \tag{7}$$

$$= w_{k|k}^{(i)} p\left(\mathbf{x}_{k+1}^{(i)} \mid \mathbf{x}_k^{(i)}\right).$$

Resampling is a crucial step in the particle filtering. Without resampling, the particle filter would break down to a set of independent simulations yielding independent trajectories with relative probabilities $w_k^{(i)}$. Since there would then be no feedback mechanism from the observations to control the simulations, they would quite soon diverge. As a result, all relative weights would tend to zero except for one that tends to one. This is called sample depletion. Research of the efficiency of different resampling techniques for CENS particle filtering is done in [7].

Here and further the following conditions will be assumed. The aircraft is performing the planned flight according to the given trajectory with known terrain field map.

The DEM data was selected for Ukrainian region and downloaded from Global Data Explorer (GDEX) web site [12].

IV. RESULTS

Here one tile is a file covering 1° × 1° Earth area. The file has 3601 rows and columns. The names of individual data tiles refer to the latitude and longitude at the geometric center of the lower-left (southwest) corner pixel. The rows at the north and south edges, as well as the columns at the east and west edges, of each tile overlap and are identical to the edge row and column in the adjacent tile.

The example of selected DEM data visualization in Matlab using built-in functions is presented in Fig. 2. Resolution of DEM data is 0.0002777777 deg, that corresponds to ~ 30 m on ground surface.

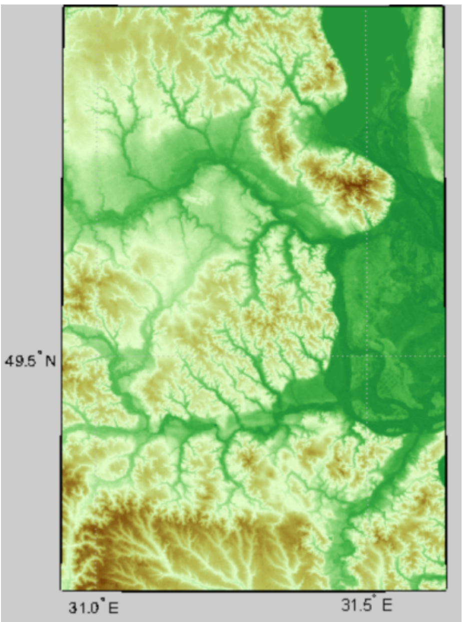

Fig. 2. Relief field of Ukrainian region used for simulation

The trajectory is set by parametric discrete equations in terms of 2D coordinates x and y:

$$\begin{aligned} x_k &= V_k \sin\psi_k + x_{k-1} + \xi_x, \\ y_k &= V_k \cos\psi_k + y_{k-1} + \xi_y, \end{aligned} \tag{8}$$

where V_k and ψ_k are speed and heading of UAV in time moment k, respectively, ξ_x, ξ_y are system noises of state vector $[x, y]$ selected here to be distributed by normal law.

The control method of aircraft lateral motion is selected to the route method when the control is performed by cross-track error between the desired track and current coordinate. The regulated parameter is track angle to be determined analytically. The simulation was performed for circular trajectory in order to estimate the quality of control and navigation by closing loop errors, that is, how precisely the aircraft is returned to initial waypoint.

The trajectory simulation was done for 300 conditional time intervals. In the time $T1$ the emergency situation was imitated, the control failure occurred due to the constructional damage because of strong turbulence and loss of the aerodynamic properties. It was also supposed that there is no satellite signal and the only one source of navigation information is INS aided by CENS.

The control failure lasted for certain period of time $T1 < t < T2$ and in time moment $T2$ the control is restored due to reconfiguration and reliable data from CENS. The control failure was realized as significant increase of noise levels ξ_x, ξ_y in (8). In time interval $T1 < t < T2$ the trajectory becomes the trajectory of random walk.

The most accurate and stable is residual resampling that is rather expected since the most probable particles (with larger weights) correspond to the best fitting of measurement to relief database and they are not lost by transition to the next step of iteration.

The results of simulation are represented in Figs 3-6.

The value of error in time of data absence was expected to be increased due to accumulation but it remains on the same level because of random nature and mutual compensation. But anyway the trajectory in the time interval $T1 < t < T2$ is tended to be the trajectory of random walk.

Algorithm with particle filtering and restoring the control was running 500 times for $T1 = 50$, $T2 = 100$, noise level increased in 5 times in order to investigate errors. Deviations ΔX, , ΔY for last 10% of trajectory were accumulated and studied. Assuming normal law of resampling errors distribution the mean and variance parameters were fitted to results of simulation using Matlab. The proposed distribution of errors is given in Fig. 7, mean values and error variances are $\mu_x = -0.1025$, $\mu_y = 0.0084$ and $\sigma_x = 0.1350$, $\sigma_y = 0.1460$.

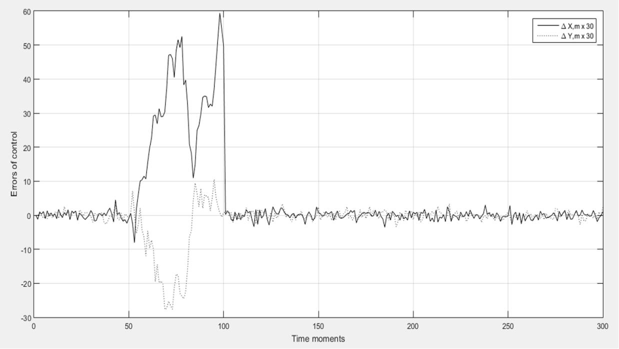

Fig. 3. Errors on the trajectory for the following parameters: $T1 = 50$, $T2 = 100$, noise level increased in 5 times

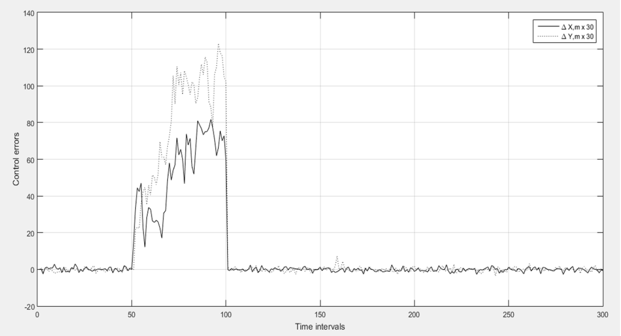

Fig. 4. Errors on the trajectory for the following parameters: $T1 = 50$, $T2 = 100$, noise level increased in 10 times

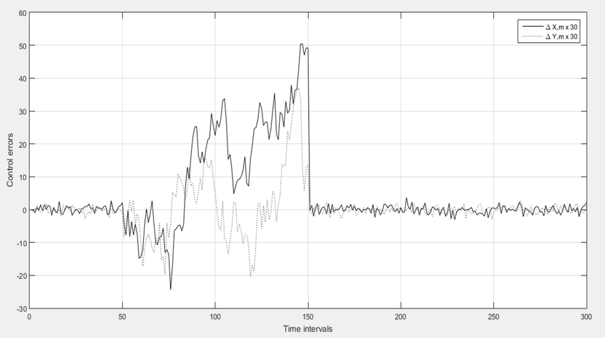

Fig. 5. Errors on the trajectory for the following parameters: $T1 = 50$, $T2 = 150$, noise level increased in 5 times

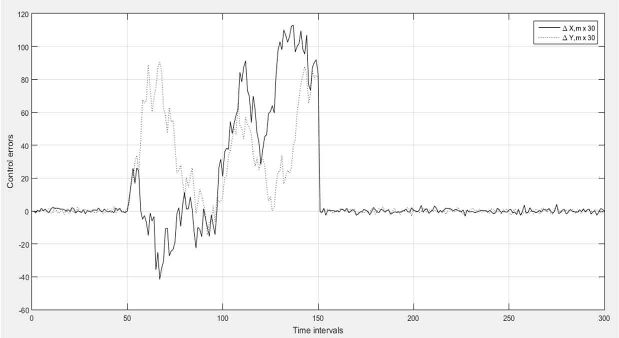

Fig. 6. Errors on the trajectory for the following parameters: $T1 = 50$, $T2 = 150$, noise level increased in 10 times

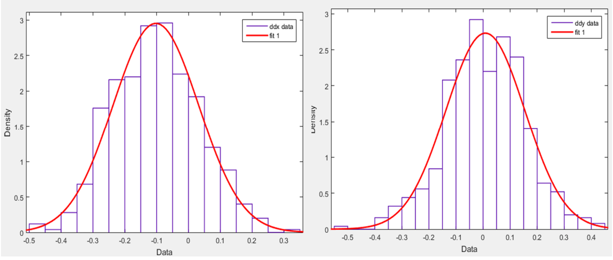

Fig. 7. Error distributions on the trajectory for the following parameters: $T1 = 50$, $T2 = 100$, noise level increased in 5 times

V. CONCLUSIONS

The proposed solution for restoring the control after constructional damage of aircraft and loss of reliable navigation data from GPS has demonstrated the acceptable quality even with increasing the time of blackout and noise level. The experiments have been conducted for terrain field with high informativity that provides the efficiency of CENS operation. Particle filtering has been proposed as basic navigation and control algorithm in order to eliminate the problems with tabulated dependence in measurement equation and preventing the accumulaion of errors for INS. Quality of control restoring has been estimated by accuracy of closing the loop in circular trajectory, i.e. the possibility of aircraft to return back in initial point in case of damage, and for 500 experiments it was in the percentage range of 13.5 … 14.6%.

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М. П. Мухіна, М. К. Філяшкін, В. М. Казак, Д. О. Шевчук. Методика точкової фільтрації для керування польотом літака у збуреному середовищі із втратою супутникового сигналу

Проблема керування літальним апаратом розглядається для певного класу ситуації, а саме коли повітряне судно потрапляє в зону, де відсутній сигнал GPS, зі значними збуреннями різного характеру, що можуть спричинити конструктивні пошкодження та навіть втрату керування. Єдиним джерелом навігаційної інформації є, наприклад, інерціальна система навігації, яка корегується від, наприклад, кореляційно-екстремальної навігаційної системи. У статті завдання керування вирішується за допомогою методики точкової фільтрації для кореляційно-екстремальної навігаційної системи із включенням вектора управління. Далі структурна конфігурація проводиться шляхом перерозподілу керування або зміни закону управління з метою створення необхідних керуючих впливів, сил і моментів, підтримання прийнятної якості управління та повернення на задану лінію шляху. Відсутність достовірної навігаційної інформації компенсується за рахунок включення в контрольний контур кореляційно-екстремальної навігаційної системи, що працює над полем рельєфу Землі. Дослідження проводилися за допомогою математичного моделювання розроблених алгоритмів у програмному пакеті MATLAB з використанням поля рельєфу (частина території Карпат). Результати довели високу точність рішення навігації та стабільність керування, оцінену похибкою на замкненій траєкторії.

Ключові слова: кореляційно-екстремальна навігаційна система; точкова фільтрація; поле рельєфу; невизначеність керування; конфігурація керування.

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М. П. Мухина, Н. К. Филяшкин, В. Н. Казак, Д. О. Шевчук. Методика точечной фильтрации для управления полетом самолета в возмущенной среде с потерей спутникового сигнала

Проблема управления летательным аппаратом рассматривается для определенного класса ситуации, а именно когда воздушное судно попадает в зону, где отсутствует сигнал GPS, со значительными возмущениями разного характера, которые могут вызвать конструктивные повреждения и даже потерю управления. Единственным источником навигационной информации может быть, например, инерциальная система навигации, которая корректируется от, например, корреляционно-экстремальной навигационной системы. В статье задачи управления решаются с помощью методики точечной фильтрации для корреляционно-экстремальной навигационной системы с включением вектора управления. Далее структурная конфигурация производится путем перераспределения управления или изменения закона управления с целью создания необходимых управляющих воздействий, сил и моментов, поддержание приемлемого качества управления и возвращения на заданную линию пути. Отсутствие достоверной навигационной информации компенсируется за счет включения в контрольный контур корреляционно-экстремальной навигационной системы, работающий по полю рельефа Земли. Исследования проводились с помощью математического моделирования разработанных алгоритмов в программном пакете MATLAB с использованием поля рельефа (часть территории Карпат). Результаты показали высокую точность решения навигации и стабильность управления, оцененную погрешностью на замкнутой траектории.

Ключевые слова: корреляционно-экстремальная навигационная система; точечная фильтрация; поле рельефа; неопределенность управления; конфигурация управления.

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