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ANALYSIS OF MODERN CORRELATION EXTREME NAVIGATION SYSTEMS

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Abstract**—***Methods of classification of correlation extremal navigation systems and geophysical fields are examined. The block diagram of correlation extremal navigation systems, which works in risk conditions of current navigational and mapping information, is introduced. The block of efficient mapping is set in the diagram; it realizes famous approach of simultaneous positioning and mapping on the base of recurrent Bayes estimation. It is shown, that block allows obtaining more precise mapping information during the flight process.*

Index Terms—Correlation extremal navigation systems; simultaneous localization and mapping; statistical-decision theory; information integration (data fusion).

I. INTRODUCTION

Navigation is executed using physical fields: determination of true heading is performed by measuring of horizontal component of Earth magnetic field; inertial navigation uses components of gravity and inertial fields; satellite navigation creates radio navigation field. It is necessary to note in most cases normal or regular components of physical field are used, unlike the concept of correlation extreme navigation, where it is necessary to have abnormal high frequency space-time fields.

Correlation extreme navigation [1] is based on the property of abnormal fields, as unique correspondence of field parameters distribution to the definite part of Earth surface.

Correlation extreme navigation system (CENS) is a system of data processing, where information is represented as random functions (fields) and is assigned for determination of coordinates of motion. These systems have such name because correlation connection between realizations of random functions is in the base of these systems work. And determination of initial values (position coordinates or their derivatives) is executed by means of search of correlation function extreme point or any other statistic estimation of random function realization.

Navigation with CENS is performed by information, obtained from geophysical fields with random structure, parameters of which are closely connected with definite parts of Earth surface.

Object control is achieved by determination of object location in the process of comparing of current (taken in process of motion) field distribution with reference distribution (taken previously) of this field, closed to the terrain with high accuracy.

Since distributions of current and reference fields by path are random processes, degree of its proximity could be determined by value of mutually correlation function. Extreme point of this function will show that current realization of field coincides with definite part of reference map of this field, coordinates of which are known with high accuracy.

II. PROBLEM STATEMENT

Analyzing the existing variants of CENS construction [1], [2], [6] it is possible to mark such common blocks:

- sensor(s) of physical field;
- mapping block;
- correlator;
- automatic optimizer;
- geo referencing block;
- rough navigation system (RNS).

Physical field sensor (Fig. 1) gives information as a current realization of field (current field representation) l_i', it could differ dependently from the method of field probing:

- point probing;
- probing along position line;
- probing by frame.

For the first variant of probing the field parameter is taken as a scalar value in every moment of time, and usage of both types of fields, such as surface and spatial, is possible. For the second variant of probing the sensor measures parameters of field along arbitrary chosen line instantaneously or during short period of time. For the third variant the parameters of field are measured from the part of Earth surface during short cycle of scanning.

Dependently on type of using field there are terrain relief of Earth surface, optical field of Earth surface, thermal field, field of coefficient of radio waves reflection (absorption) – field of radar contrast, magnetic field of Earth, gravity field of Earth and others.

Literature analysis [2], [3], [4] allows to formulate next characteristics of geophysical fields classification from Table.

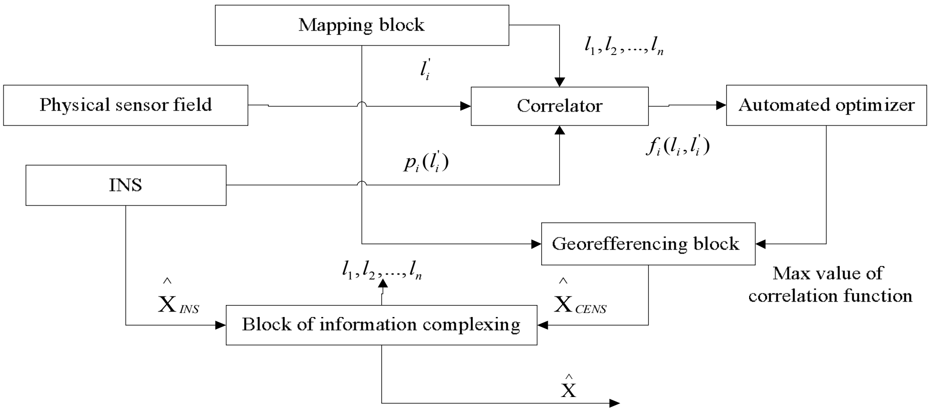

Fig. 1. General CENC block diagram

Geophysical fields classification

According to physical origin	According to spatial structure		According to forming principle		According to representation on the map				According to type of measurable signal		
	Spatial	**Surface**	**Artificial**	**Natural**	**Analytical model**	**Isolines**	**Regular grid**	**Irregular grid**	**Temporary**	**Spatial**	**Spatitial-temporary**
Relief field		✓		✓		✓	✓	✓	✓	✓	✓
Optical		✓		✓			✓			✓	✓
Heating		✓		✓		✓	✓		✓	✓	✓
Radar contrast		✓	✓				✓		✓	✓	✓
Magnetic	✓			✓	✓	✓			✓		
Gravity	✓			✓	✓	✓			✓		

Mapping block contains the information about reference realization of field $l_1, l_2, ..., l_n$ which can be represented as regular of irregular grids, isograms or analytical model.

Correlator, dependently on the kind of CENS, could calculate the value of correlation function $f_i(l_i, l'_i)$ for every reference, stored in the memory (searching CENS), or in the case of RNS presence or priory known flight path, calculate correlation function only for one reference (non-searching CENS).

In the last case, the presence of automatic optimizer is not necessary, because there is no necessity to find extreme point of correlation functions of pairs of reference and current realizations of field.

According to the type of used RNS the construction of CENS could be distinguished by the degree of structural connectivity of systems and algorithms of combination of navigation information. Since CENS on its own could not be unique and main source of navigation information for the majority of moving objects, including unmanned aerial vehicles (UAV), in future we will use term interoperable navigation system (INS) instead of term RNS. Taking into account the errors of interoperable navigation system (INS), the priory probability of object position, as a probability of coincidence of current field realization with some reference $p_i(l'_i)$, is in the input of correlator. Also the estimation of state vector $\hat{\mathbf{X}}_{INS}$ goes from the output of INS to the block of information combination, and vector becomes more accurate by means of preliminary navigation information from CENS from the block of geo referencing $\hat{\mathbf{X}}_{CENS}$.

Let's designate classification attributes of CENS and formulate general requirements to the structure of the system with presence of inaccurate mapping information or large errors of measuring instruments and INS.

III. ANALYSIS OF EXISTING CENS CLASSIFICATIONS

Main classification attributes for CENS analysis were formulated in [2]. Let's consider those, which are important for CENS construction in conditions of risk and uncertainty of mapping information and sensors readings.

Attributes, according to which CENS are classified, define all possible kinds of its components realization and features of used data processing algorithms – methods for calculation of correlated functions and determination of function extreme point, size and methods of priory information usage.

1. According to the type of used geophysical field there are CENS of surface and spatial type.

2. According to the type of working information there are CENS with point probing, probing along the line and frame probing.

3. According to the size of mapping information there are systems with memory and without it. Systems without memory are systems, in which reference field realizations are fixing in the moment of CENS functioning (correlation measuring instruments of speed). Such systems could define only speed of airplanes coordinates change according to the landmarks, using any surface fields, including unstable in time fields (for example, clouds). Systems with memory have priory (reference) information about geophysical field, and this information is cumulated before the functioning beginning. In CENS with minimal priory information in onboard memory device the information about coordinates of some landmarks (point and contour), located along the line of the desired path, is saved.

Systems with not full priory information foresee the correction of navigation complexes by point and contour landmarks, and continuous correction on separate parts of the path; these paths have indices of one or some geophysical fields for correlated extreme navigation.

4. According to definition of extreme point of correlation function the heuristic, non-searching, searching and combined systems exist. If priory it is known that during the flight relatively small deviations of parameters of UAV motion from nominal parameters could take place, and non-agreement between current and reference images does not exceed the radius of correlation of their mutual spatial correlation function, then non-searching CENS have advantage. Searching CENS, having the peculiarity of invariance respectively to initial errors, are more universal, but at the same time they are more difficult in comparison with non-searching CENS. Searching and combined methods of determination of correlation function extreme point operate by concept of risk in choice of optimal hypothesis of object location dependently on field sensor errors and incompleteness of mapping information.

5. By the method of data storage and data processing there are analogue, digital and analogue to digital systems. Nowadays digital storage and data processing devices are used, and this classification could not be taken into account.

Scheme of CENS classification is represented on Fig. 2.

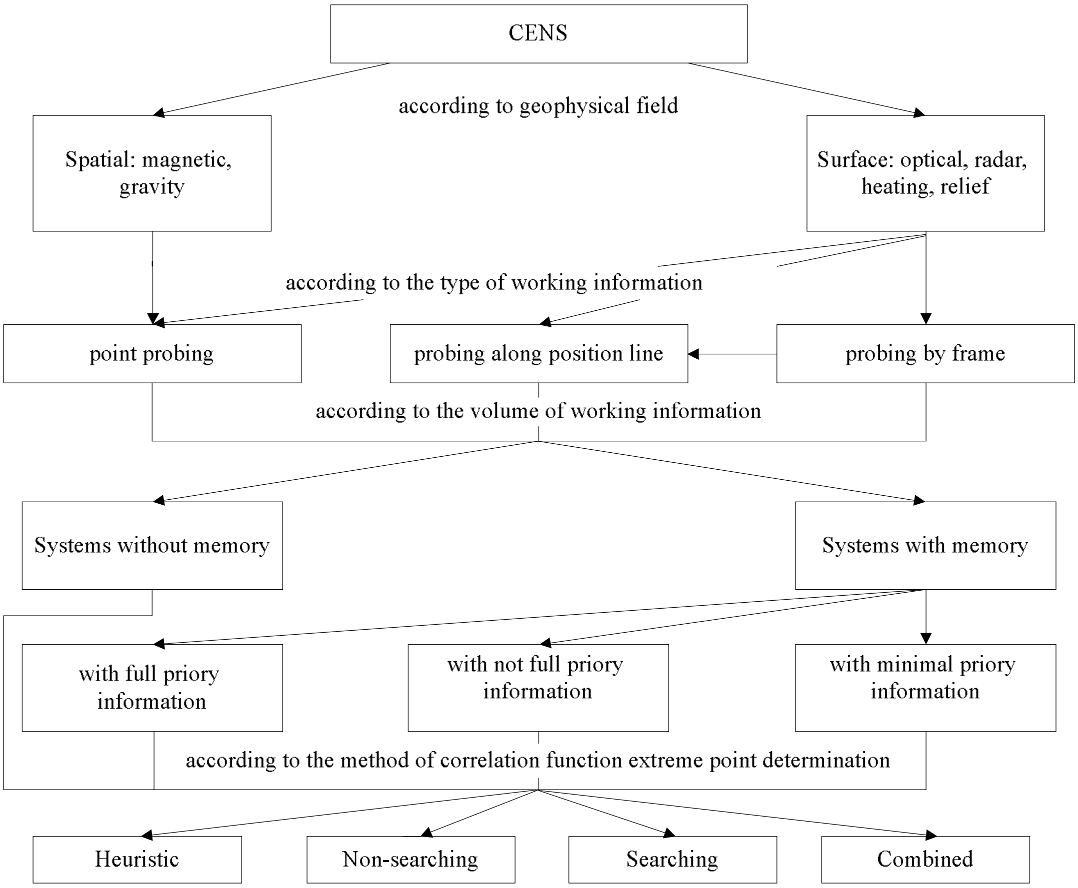

Fig. 2 CENS Classification

IV. DEVELOPMENT OF BLOCK DIAGRAM OF CENS, WORKING IN RISK AND UNCERTAINTY CONDITIONS

In the case of use of searching and combined methods of correlation function extreme point determination the hypothesis about possible location of moving object according to INS are checked [2, p. 196-202]. Confidence of every hypothesis is defined by functional value as a measure of proximity between realization, obtained during the flight, and realization of field, taken from the memory of mapping block. At the presence of large inaccuracies of mapping information the risk of erroneous hypothesis acceptance will increase, and correction of map will be necessary.

For optimal hypothesis search D_i the Bayesian solution is applied, it minimizes the average risk $R(F)$ of mistaken choice of hypothesis. Deterministic crucial function is written as [2]:

$$F(D|Z)=F^0(D|Z)\sum_{i=-n}^{n}\delta(D-D_i), \qquad (1)$$

where $\delta(D-D_i)$ is delta-function; $Z=l+\delta l$ is input of the signal (current realization of field, distorted by noises); $L_i(i=-n,...,n)$ is reference realization of field on the part of the path. Average risk under condition of known laws of distribution of INS errors will be [2]:

$$R(F)=\int_{\Gamma}\sum_{i=-n}^{n}\sum_{j=-n}^{n}W_{ij}p_iP(Z\,|\,L_i)F^0(D_j\,|\,Z)dZ, \qquad (2)$$

where W_{ij} is a function of losses at acceptance of j^{th} hypothesis D_j, if at the input there is i^{th} signal; $P(Z\,|\,L_i)$ is a likelihood function, integral (2) is taken according to input spaces; p_i is priory probability L_i, known due to law of distribution Δ of INS errors:

$$p_i\int_{i\Delta l}^{(i+1)}p(\Delta)d\Delta,$$

where Δl is interval of discreteness of representation of reference realization of field.

If the input Z is accepted, and crucial rule chose hypothesis D_i , then $F^0(D_\nu\,|\,Z)=1, F^0(D_j\,|\,Z)\underset{j\neq\nu}{=}0$ and integrand in (2) is defined in the following way:

$$A_\nu=\sum_{i=-n}^{n}W_{i\nu}p_iP(Z\,|\,L_i)\,. \qquad (3)$$

If the solution is optimal, then $A_\nu=\min\limits_{i=-n,...,n}A_i$. And rule of optimal solution follows from here: according to accepted input Z all numbers A_i are defined, and such hypothesis D_ν is chosen, for which A_ν will be minimal.

So, the problem is formulated in the theory of statistic decisions. Let's consider the case, when during the minimization of integrand in (3) the values A_i were obtained, these values do not satisfy some confidence threshold ε . Incompleteness of mapping information, large noisiness of field sensors, failure in CENS performance etc are the reasons of this. In this case it is necessary to specify the mapping information, which we have, using the block of efficient mapping.

Principle of its action is based on famous approach of simultaneous localization and mapping SLAM, the sense of it is creation of terrain map by means of searching of tyFigal peculiarities of environment, marking them as landmarks, determination of their coordinates using navigation system of dead reckoning (odometric, inertial), localization of moving object according the landmark, further specification of mapping information by means of repeated observations of these landmarks from other point. Abnormal components of geophysical fields, defined directly during the flight, can be tyFigal peculiarities of environment.

Probabilistic formulation of SLAM problem is in the current determination of probability distribution of object position **X** and position **M** of some landmarks (in our case, anomalies of geophysical field) by means of accumulation of measurements **Z**. Going to discrete time of measurements, the problem statement of SLAM can be formulated as a problem of recursive Bayesian estimation:

$$p(x,m\,|\,z_k)=\frac{p(z_k\,|\,x,m)p(x,m\,|\,z_{k-1})}{p(z_k\,|\,z_{k-1})}.$$

Depending on the choice of probability distribution law and field information signs representation, i.e. landmarks, problem solution (3) can be executed using expended Kalman filter [5] or particle filter (Rao-Blackwellized Particle Filter).

In the composition of introduced block of efficient mapping, except SLAM procedures, realization of algorithm of extraction of informative signs and their following matching to the terrain using INS information must be included.

Achieving the set minimal level of risk in (2), the cycle of specification of mapping information (Fig. 3) finishes the performance and data of block of efficient mapping are transmitted to mapping block.

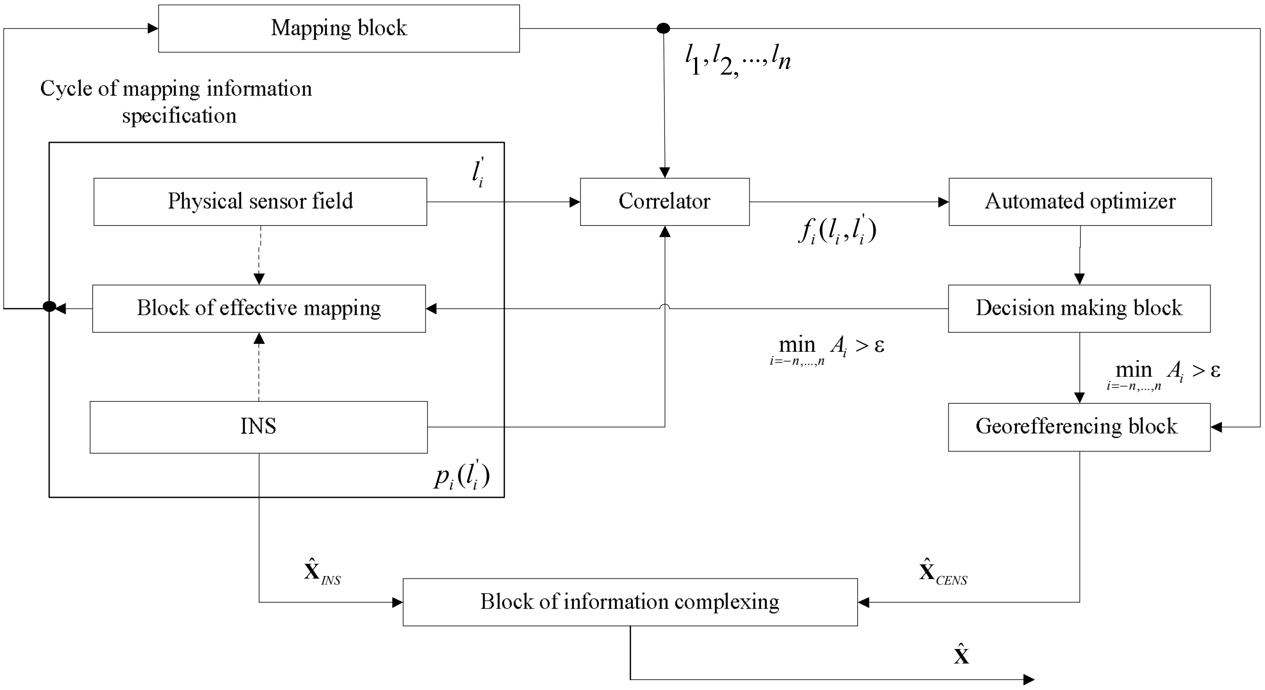

Fig. 3. Block diagram of CENS with effective mapping block

Let's consider realization of introduced algorithm on the example of CENS of optical field of the Earth, in which key points of image (landmarks) are defined during the scanning, coordinates of these points are known from aerial photos or satellite terrain maps. Confidence interval of location of UAV is defined by INS error. Discreteness of landmarks coordinates determination is defined by degree of mapping detail and camera resolvability.

During defining the key point the distance to it ρ and azimuth θ are calculated, cumulatively with knowing the coordinates of the point (x_i, y_i) it gives the possibility of definition of object coordinates by known formula

$$x = x_i + \rho_i \cos\theta_i, y = y_i + \rho_i \sin\theta_i,$$

where index corresponds to the order of key point. Therefore measurement vector in (1) represents the parameters of key points $\mathbf{Z} = \left[(\rho_1, \theta_1), (\rho_2, \theta_2), ..., (\rho_N, \theta_N)\right]^T$, under reference signal we understand coordinates of the key points in introduction of *j*th hypothesis $\mathbf{L} = [(x_1, y_1), (x_2, y_2), ..., (x_N, y_N)]^T$ of finding the object in the point, which is obtained at combination of measured and reference location of the key points. Dependence between the vectors **Z** and $\mathbf{L}_j$ is described by:

$$\rho_i = \sqrt{dx_i^2 + dy_i^2},\ \theta_i = \arctan\frac{dy_i}{dx_i},$$
$$dx_i = x_i - x,\ dy_i = y_i - y.$$

Assuming the point peculiarities of field are not correlated between each other, with errors during coordinates determination, distributed according to normal law, likelihood function (3) could be written in the following way:

$$P(Z \mid L_j) = \frac{1}{\left(\sqrt{2\pi}\sigma_\Sigma\right)^N} \exp\left(-\frac{\left\|Z - L_j\right\|^2}{2\sigma_\Sigma^2}\right),$$

where σ_Σ is standard deviation of diagonal covariance matrix of noises for every key point (in assumption, that correlation between measurements of every point is not present).

At acceptance of simple function of losses $W_{ij} = \begin{cases} 1, & i \neq j, \\ 0, & i = j. \end{cases}$, the value $p_j P(Z \mid L_j)$ could be replaced by posteriori probability $P(L_j \mid Z)$ after measurement execution. Thus, optimal hypothesis is defined according to maximum value of posteriori probability

$$P(L_j \mid Z) = \frac{1}{\left(\sqrt{2\pi}\right)^N \sigma_\Sigma} \times \exp\left(\frac{-\|Z\|^2 + 2\left(ZL_j\right) - \left\|L_j\right\|^2 + 2\sigma_\Sigma^2 \ln p_j}{2\sigma_\Sigma^2}\right). \tag{4}$$

Having the block of efficient mapping, which increases the number of key points, the growth of posteriori probability (4) is observed, but only to definite moment. After the peak (Fig. 4) the probability of determination of right hypothesis begins extremely decreasing, because simultaneously with increasing of key points the cumulative error of measurements σ_Σ also increases. So, at preliminary analysis the determination of optimal number of key points for reliable localization is possible.

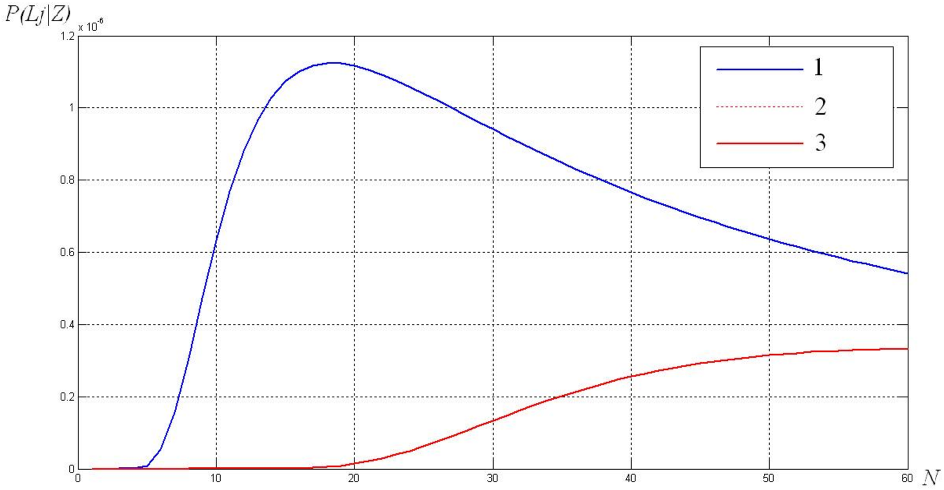

Fig. 4. Dependence of posteriori probability on the quantity of key points and total error of its determination (1 is true hypothesis, 2 and 3 are false)

V. CONCLUSIONS

Correlation extreme navigation systems structure and methods of classification of its existing realizations are analyzed. CENS block diagram, working in risk conditions of current navigation and mapping information, is proposed. Implementation of block of efficient mapping, realizing the famous approach of simultaneous localization and mapping on the base of Bayesian estimation, will allow the specification of mapping information directly during the flight.

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М. П. Мухіна, І. В. Седень. Аналіз сучасних кореляційно-екстремальних навігаційних систем
Розглянуто способи класифікації кореляційно-екстремальних навігаційних систем і геофізичних полів. Представлено структурну схему кореляційно-екстремальної навігаційної системи, яка працює в умовах ризику поточної навігаційної та картографічної інформації. В схему введено блок оперативного картографування, що реалізує відомий підхід одночасного позиціонування і картографування на основі рекурсивного байєсовського оцінювання. Показано, що блок дозволяє уточнення картографічної інформації безпосередньо під час польоту.
Ключові слова: кореляційно-екстремальні навігаційні системи; одночасне позиціонування та картографування; теорія статистичних рішень.

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М. П. Мухина, И. В. Седень. Анализ современных корреляционно-экстремальных навигационных систем
Рассмотрены способы классификации корреляционно-экстремальных навигационных систем и геофизических полей. Представлена структурная схема корреляционно-экстремальной навигационной системы, работающая в условиях риска текущей навигационной и картографической информации. В схему введен блок оперативного картографирования, реализующий известный подход одновременного позиционирования и картографирования на основе рекурсивного байесовского оценивания. Показано, что блок позволяет уточнение картографической информации непосредственно во время полета.
Ключевые слова: корреляционно-экстремальные навигационные системы; одновременное позиционирование и картографирование; теория статистических решений; комплексирование информации.

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