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MODEL OF HIGH-PRECISION CONTROL SYSTEM OF HIGH-SPEED AIRCRAFTS

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A generalized model is proposed – a structural scheme of a high-precision control system based on the integration of the inertial navigation system and the correlation-extreme navigation system of high-speed aircrafts based on land-based targets. The algorithm of high-precision control system functioning is considered. The basic tactical and technical requirements for passive radiometric correlative-extreme systems of millimeter band, correcting the errors of the inertial navigation system, are analyzed. It is shown that the accuracy of the determination of the mutual coordinates of high-speed aircrafts and ground-based objects as a result of the application of navigation systems over the external surface field of the Earth – radio-thermal contrast, is a few meters. Examples are given of the technical implementation of matrix radiometric systems in the millimeter band, which ensure the required speed of operation of systems of the order of fractions of a second. The tactics of using a high-precision control system for high-speed aircraft are considered.

Keywords: high-speed aircraft, high-precision control system, inertial navigation system, correlation-extreme navigation system, millimeter band.

INTRODUCTION

The presence on the high-speed aircraft as part of the on-board control system (CS) as the main – inertial navigation system (INS) allows you to bring the aircraft into a specified area of space, that is, to solve the navigation problem [1]. One of the main characteristics of navigation systems is the accuracy of measuring the current coordinates of the aircraft during the flight along a given trajectory. An estimate of the accuracy of the INS is the magnitude of the mean square deviation (MSD) of the actual flight path of the aircraft from the target.

The main contribution to MSD onboard CS is made by the so-called instrumental and methodological components of error. Instrumental errors CS include the errors of INS instrument complexes. Methodical errors are due to the peculiarities of methods and control algorithms implemented by CS. So, at a range of several hundred kilometers, the value of the MSD control system based on command instruments (gyroscopes, accelerometers) INS is hundreds of meters [1]. At the same time, the required accuracy of the removal of the aircraft, depending on the tasks performed, lies within tens or even units of meters [1].

Analysis of literature. One of the ways to improve the accuracy of the positioning of the aircraft is the integrated use, along with INS, of additional corrective information retrieval systems, including information signs of land-based objects directly-navigational aids.

It is possible to integrate INS with the receiving equipment of the global satellite navigation system (NAVSTAR, USA, GLONASS, Russia) using the public channel. However, as analysis shows, this does not ensure the required accuracy of the launch of the aircraft in a given area [2]. In addition, the use of signals from the Navstar system violates the principle of autonomy of the use of aircraft. Implementation of this principle is especially important for high-speed military aircraft (aircraft, ballistic and covered missiles), performing a combat mission in real-time conditions.

Another way to improve the accuracy of navigation is to equip the aircraft control system with external field sensors. Space fields (anomalous magnetic field of the Earth, gravitational field), as well as surface fields (field of relief, optical or radar contrast) are used as external fields for navigating flying machines.

Due to the fact that the spatial fields have a large correlation radius in comparison with the dimensions of the object of navigation (aircraft), information sensors of the correcting systems of the aircraft use surface fields – characteristics of the relief field, optical, infrared radiation, as well as radar reflection or natural radiation of navigation objects, respectively, in the visible, infrared and radio wave bands.

Promising in this regard are the recently developed correlation and extreme systems (CENS) for high-precision navigation of high-speed aircraft. CENS of different wave bands [3–7] operate on the principle of combining the current images (CI) generated on board the aircraft and the reference images (RI) of ground navigation objects synthesized in advance and stored in the on-board special calculator (SC) memory.

Based on the results of combining the images, the coordinates of the extremum of the criterial function are found, which is the unknown error value – the correction «zeroing» the error of the inertial navigation system.

The choice of this or that class of an additional navigation system depends on the system's tasks and, as a consequence, on the possibility of providing the system with complex, often contradictory tactical and technical requirements (TTR).

The integrated use for the navigation of aircraft INS and CENS allows reducing MSD (σ) inertial CS to the amount of error provided by CENS.

The flight control system of the aircraft in the case of the integration of various navigation systems, leading to an increase in the accuracy of the system as a whole, becomes high-precision control system (HPCS).

Synthesis of HPCS is fraught with difficulties in integrating navigation systems of different classes, and the need to quantify the efficiency and effectiveness of the entire system (accuracy, reliability, immunity and noise immunity of HPCS).

Purpose of the article is to justify the principles of construction – to create a model for the operation of a high-precision control system for high-speed aircrafts.

1. PRINCIPLES FOR THE CONSTRUCTION OF A HIGH-PRECISION CONTROL SYSTEM FOR HIGH-SPEED AIRCRAFTS

Analysis of the results of the studies [8, 9, 11] allows us to present the process of functioning of HPCS by aircraft in the form of a generalized structural scheme, shown in Fig. In HPCS, the main mode of operation is autonomous control, performed according to the coordinates calculated in the INS. (The components of the velocities of translational motion of the center of mass and rotational motion around the center of mass of the aircraft are not considered for simplicity).

A feature of inertial sensors (accelerometers and gyroscopes) is the ability to accumulate an error over time. This leads to the need for correcting the calculated coordinates at intermediate stages of flight of the aircraft. Consider application as corrective systems – perspective correlation-extreme navigation systems.

Foreign equivalents Correlation-Extreme Navigation System. Below are the main characteristics of CENS, which are currently used as correcting systems for INS aircraft.

TERCOM is a relief centimeter band CENS for navigating cruise missiles in which a single-beam radio altimeter is used as an external field sensor combined with a barometric altimeter [6].

RAC and DIGIRAC – radiometric (RM) area correlator for navigation and guidance of aircraft (Tomahawk cruise missiles) 8 mm band. The RAC navigation system performs a one-shot scan of the frame at a rate of 14 lines/s, within 50 degrees in azimuth, 80 degrees in elevation, the antenna's beam width is 2 degrees. In the DIGIRAC system, digital image processing is performed [6, 7].

Radiometric CENS MICRAD 8 mm band, in which an antenna system with a 4-beam radiation pattern located perpendicular to the direction of motion of the aircraft is used to form the image «frame» [8].

CENS ATIPUS infrared band, wavelength (3–5) μk performs a fast single-shot horizontal scan of the frame [8].

Optical digital CENS DIGISMAC is equipped with a television camera with a variable focal length, digital image processing [8].

The radar CENS RADAG is 2 cm in range, equipped with an incoherent pulse radar, which performs circular scanning of the beam of the antenna pattern at a speed of 2 rev / s.

It should be noted that the complex application of the above CENS is possible.

To perform the correction (Fig. 1) in the memory of the Reference Image (Maps), matrixes of terrain sections are entered, on which correction is made.

The number, dimensions of the Reference Image sections can be different.

Thus, in the relief metric CENS TERCOM, up to 20 reference maps with dimensions from (20×20) km are used for the initial stages of correction, up to cards of size (1×1) km or less. In this case, the dimensions of the elementary sections of the maps can vary from (122×122) m up to (30×30) m [6].

In the radar (centimeter wave band) CENS RADAG, four sets of reference maps are used for four different flight heights [6, 7].

In the radiometric (millimeter wave) CENS RAC, the reference map contains 100×100 the resolved elements, the angular dimensions of one resolution element are 2^0 [6, 8].

2. ALGORITHM FOR THE OPERATION OF HIGH-PRECISION CONTROL SYSTEM

The principle of functioning of HPCS is as follows (Fig. 1). When the area of the first coordinate correction X_k, Y_k is reached, a radio altimeter or / and a barometric altimeter (RA, BA) are activated, which determine the height of the first reference to the ground navigation landmarks H_k. The altitude data H_k is transferred to the Memory of the RI, from which the RI scaled for this height enters the on-board special calculator (SC).

External Field Sensor on the INS command provides (X_k, Y_k) an overview of the earth's surface, resulting in the formation of the current image, which is converted in the analog-to-digital converter (ADC) into a digital CI. The digital CI comes in Memory of the Current Image (Maps), from the output of which the two-dimensional CI enters SC to calculate the functional (the two-dimensional correlation function RI and CI) and the search for the extremum of the criterion function.

After finding the extremum of the functional, the received errors in the measurement of the coordinates of the aircraft $\Delta X_k, \Delta Y_k$, together with the current coordinates of the aircraft X_k, Y_k (from the INS) and altimeter data about the current flight altitude H_k, enter the measuring

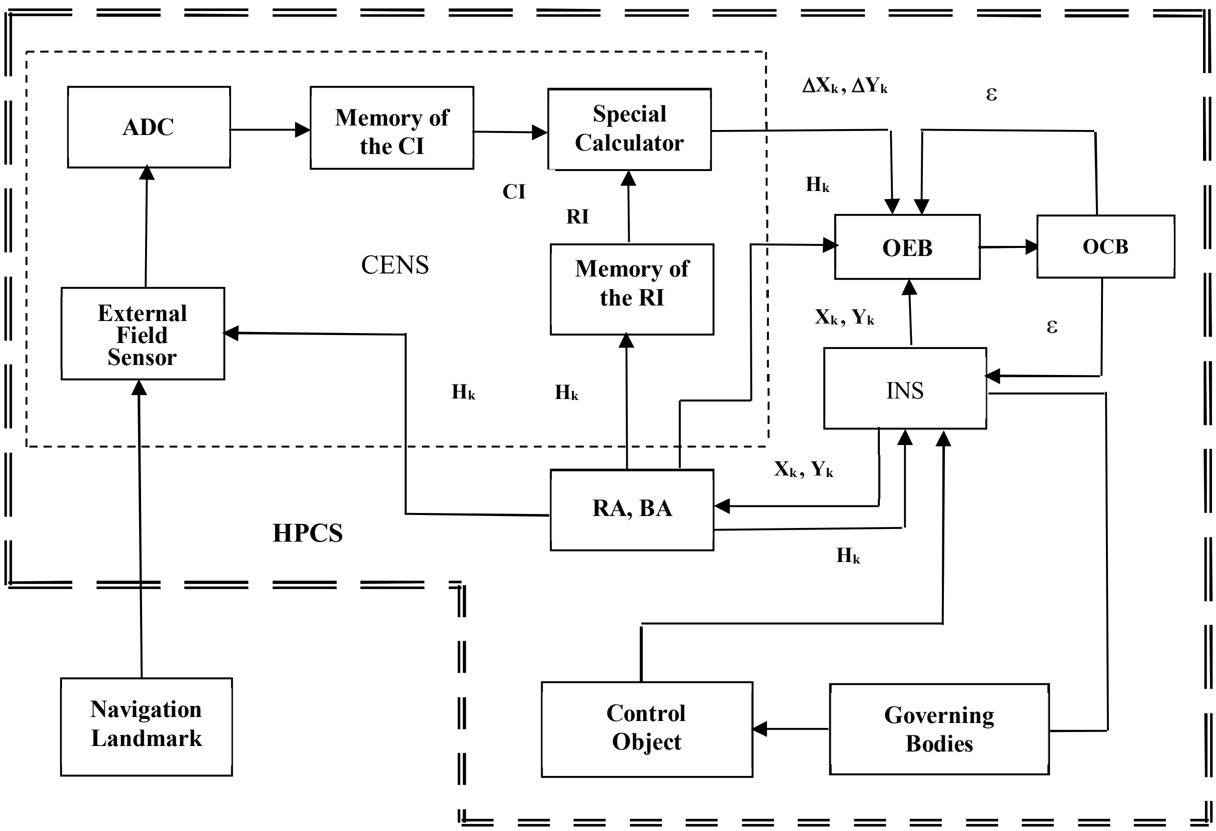


Fig. 1. Generalized structural diagram of a high-precision control system for high-speed aircrafts

device – the optimal estimation block (OEB) (in the case of the linear estimation system, the Kalman filter) optimal estimation of such INS characteristics as: deviation angle of gyro-stabilized platform (GSP) from local vertical $\hat{\alpha}$, angular velocity of GSP departure $\hat{\omega}$, error of position measurement $\Delta\hat{x}$ and speed of motion aircraft $\Delta\hat{V}$.

Further, these estimates are fed to the optimal control block (OCB), which generates a correction signal ε in the form of a sum of all estimated errors weighted with variable coefficients. The feedback correction signal ε is fed to the inputs of the first and second integrators of the INS, as well as to the correcting motors of the GSP, and in order to give the INS astaticism with respect to the constant component of the drift GSP, corrective motors of the GSP are supplied with both a signal proportional to the positional error and an integral of this errors.

Thus, the so-called three-point correction scheme INS is realized [4]. The correction signal ε also enters the integrating circuits of the optimal estimation block (in the Kalman filter).

Formed by the INS team come to the governing bodies, which change the flight path of the aircraft. There is a feedback between the control object (aircraft) and INS, which allows to eliminate the navigation errors that are not compensated for one measurement cycle.

After the end of the first stage of correction, new coordinates are formed X_k, Y_k in the INS, for the second stage of the correction of the trajectory of the aircraft. During the period between the first and second correction, an autonomous flight of aircraft is performed by INS commands. All further correction procedures are performed similarly.

The ultimate goal of the control is to bring the aircraft to a given point in space with minimal errors in measuring the coordinates X_k, Y_k and the current altitude of the flight H_k.

The main Tactical and Technical Requirements for CESN [8, 9]:

1. The accuracy of the determination of the mutual coordinates of the aircraft and the ground target object is a unit of meters.
2. Weatherproofness – reliable operation of the system in unfavorable weather conditions.
3. Performance – units – fractions of seconds.
4. Stealth and noise immunity of systems.
5. Small overall-mass and cost characteristics of onboard equipment.

These requirements must be considered from the point of view of the task performed by the aircraft. Considering that high-speed aircrafts (rockets, shells, supersonic aircraft, etc.) that carry out the dual purpose mission (navigation, aiming at the target) are considered, higher requirements for stealth systems and all-weather performance are imposed on the sensors of external information of this class of aircraft.

As analysis of the results of many studies shows [6-8, 10], passive radiometric systems of millimeter range meet these requirements. To this there are the following prerequisites.

The components of the concept of «noise immunity» are concealment of operation and noise-stability of receiving devices with respect to noise and external interference.

Passive RM systems, in comparison with active radar systems, provide high energy concealment due to the work «only on signal reception». The noise immunity of the operation of PM systems is provided by the application of known methods and devices for interference compensation at the input of receiving devices [8].

MMD systems with subband $\lambda = 8$ mm and $\lambda = 3$ mm («atmospheric transparency windows»), in comparison with systems of visible and infrared bands, are able to function in adverse weather conditions, in fumes and dust formations, day and night.

One of the basic requirements for weapons detection and targeting systems is the requirement to ensure high accuracy in determining the mutual coordinates of the aircraft and the target ground target object.

The accuracy characteristic is the mean square deviation (MSD) of the flight path of an aircraft from a given one. MSD is determined based on the required value of the probability of bringing the aircraft into a specified area of space and accuracy (MSD) of the inertial navigation system. The size of the MSD is also determined by the size and configuration of the objects being sighted on the earth's surface, the technical characteristics of the CENS (primary signal processing) sensors, the image processing algorithms (methods and means of secondary processing) used.

The angle of the «field of view» of the information sensor CENS should «cover» the area of the earth's surface, corresponding to the error of the aircraft output to a given area of space with the help of INS. The sensor CENS must have a high resolution, both in space and the measured signal parameter (by the intensity of the signal reflected or emitted by the object).

Although radio-frequency systems have a lower spatial resolution than visible-band systems, calculations show [8] that millimeter-band radiometric CENSs provide the required MSD values of the order of meters.

Ensuring the required small overall mass characteristics of CENS on-board equipment involves the creation of transceiver equipment systems with the attraction of a modern element base. Thus, the CENS MMD transceiver equipment is created on a solid-state element base, commercially produced by the domestic industry, is small and relatively light. The dimensions of the equipment are limited (do not exceed) the size of the antenna system [10].

In evaluating the cost of CENS equipment, it is first of all necessary to proceed from the importance of solving the problem of navigating the aircraft with high accuracy. The importance of the task predetermines the choice of CENS of a certain class, or the need for the joint application of CENS of different classes.

The above requirements for imaging systems of ground-based navigation objects on board a high-speed aircraft cannot be met if the requirement for high performance of the systems is not fulfilled.

Thus, for example, with the flight speed of an aircraft of the order of (2–3) M (M – Mach number, speed of sound), the time taken for the onboard CENS and HPCS as a whole consists of the time of the current image formation, comparison of the current image with the reference one, finding the coordinates of the extremum of the solving function of the image alignment algorithm and error compensation (MSD) of the inertial navigation system, and is less than 1 s [6, 7].

To ensure such a high speed are capable of multichannel, so-called matrix systems. Let us consider an example of constructing a matrix radiometric system.

In [8], an example is given of calculating the electrical characteristics and geometric dimensions of a multi-beam two-mirror antenna with a matrix group irradiator.

The basis for the calculation is a two-mirror Cassegrain antenna (Fig. 2) with a diameter of the main mirror – a reflector d = 300 mm at $\lambda = 8{,}6$ mm the wavelength.

The following results were obtained during the calculation. The maximum dimensions of the group $8\times8 = 64$ irradiator by the dimension of the elements, under the condition of constructing a group irradiator in the form of a waveguide holder, the open ends of which are complemented by dielectric tapered rod inserts (Fig.4), constitute (over the large wall of a standard waveguide $a \times b = 7{,}2$ mm×3,4 mm) is $d_{ir} = 57{,}6$ mm.

The dimensions of the notch in the reflector correspond to the dimensions of the group irradiator along the large wall of the waveguide, which is smaller than the diameter of the sub reflector L = 60,9 mm.

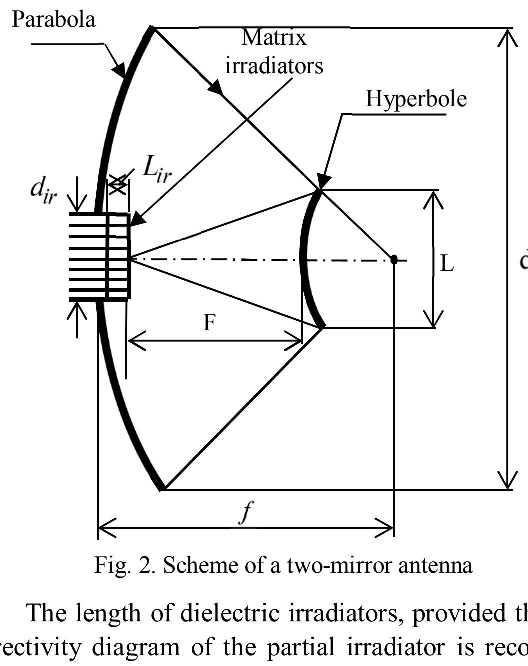


Fig. 2. Scheme of a two-mirror antenna

The length of dielectric irradiators, provided that the directivity diagram of the partial irradiator is reconciled with the dimensions of the sub reflector (the absence of «overflows» beyond the edges of the sub reflector) is $L_{ir} = 25{,}8$ mm. In this case, the distance from the phase center of the irradiator to the top of the sub reflector F = 43,6 mm, that is, the irradiator can be structurally placed between two mirrors. Shading by the sub reflector of the main mirror-reflector, by the ratio of the areas, on 4,13 %, does not significantly reduce the directional effect of the primary mirror, which is $G \geq 7\times 10^3$. The width of the directivity diagram of the partial rays is $2\theta^0_{0,5}=2^0$.

On Fig. 3 Radiometric straight receiver gain 8 mm band.

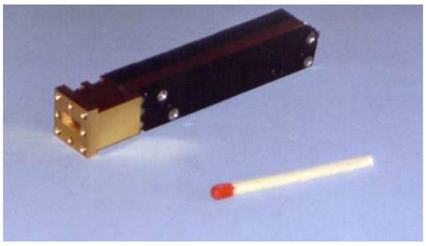


Fig. 3. Radiometric straight receiver gain 8 mm band

On Fig. 4 are presented dielectric rod in a multi-element antenna.

Fig. 5 shows a radiometric receiver with a direct gain of 3 mm band.

Fig. 4. Use of tapered dielectric rod in a multi-element antenna

Fig. 5. Radiometric straight receiver gain 3 mm band

In Table 1 are presented characteristics of Radiometric straight receiver gain 8 mm band (Fig. 3).

Table 1

Characteristics of Radiometric straight receiver gain 8 mm band

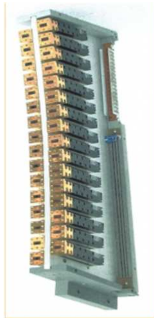
Frequency band, GHz	33…38
Sensitivity, mK/√Hz	≤ 10
Dimensions, mm	60x14x14
The weight, g	40

In Fig. 6 are showing parabolic and lance antenna with matrix dimension.

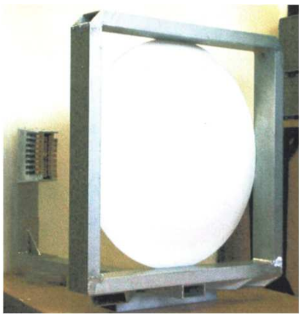
In Fig. 7 are showing radiometric image and foots NPP «Saturn», received matrix RM.

The analysis allows drawing a conclusion about the principle possibility of practical implementation of matrix navigation systems based on passive radiometric sensors of millimeter range with the required characteristics.

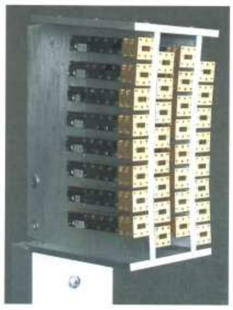
a)



b)



c)



d)

Fig. 6. Parabolic (a) and Lance (c) antenna with matrix dimension (b), (d)

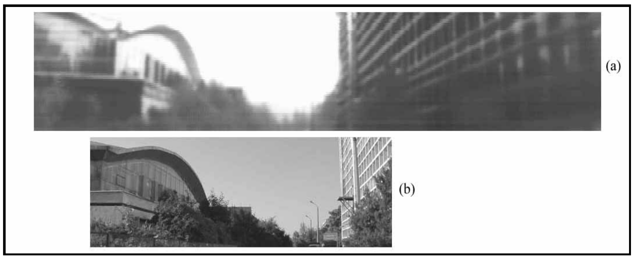


Fig.7. RM image and foots JSC NPP «Saturn», received matrix RM (Fig.5)

Stages of synthesis of the structure of correlation-extreme navigation system. The analysis of TTR, presented to CENS, allows formulating the main stages of synthesis of the structure of CENS.

At the first stage, a choice is made of the type of information sensors that meet the requirements for navigation accuracy, all-weather operation, performance, speed, noise immunity, overall dimensions and cost.

At the second stage of the synthesis of the CENS structure, it is necessary to develop image processing algorithms and a technique for synthesizing reference images of navigational objects corresponding to these algorithms on various backgrounds, satisfying the requirements for the efficiency of synthesis and updating of RI for various flight conditions of aircraft.

The third stage of CENS synthesis is the development of the structure of the special calculator, the requirements to which are determined based on the results of the first and second stages (complexity of the processing algorithms and information capacity of RI and CI), as well as the requirements for information processing speed and reliability of the CENS operation as a whole.

3. APPLICATION TACTICS COMPLEX CONTROL SYSTEMS

High-precision control systems, depending on the tasks performed by aircrafts and aircraft classes, can be conditionally divided into the following types.

1. Aircraft single-use (guided missiles, projectiles) must be equipped with HPCS, representing a combination of INS and CENS visible or infrared, or millimeter band of electromagnetic waves. The choice of the wave band depends on the state of the weather conditions (low clouds, fogs) and the smoke of the atmosphere (the presence of fumes, dust formations, and the limitation of optical visibility) in the area of the location of land-based objects – navigational reference points.

Data on the state of weather conditions should be provided by the preliminary intelligence systems on the state of smoke.

2. Aircraft reusable (aircraft, unmanned aircraft) can be equipped with HPCS, representing a combination of INS, as well as CENS of visible (IR) and millimeter wave bands. The decision to apply CENS of this or that range or several ranges in the complex (the sensor of the visible range + IR sensor + MMD sensor) is accepted by the operator (pilot) or autonomously on-board special calculator from weather conditions and smoke from the visible range sensor.

CONCLUSIONS

An analysis of the functioning of HPCS showed the principal possibility of integrating INS and CENS.

In this case, preference should be given to CENS, equipped with passive information sensors of the external field: optical and infrared sensors, in the case of systems operating in a cloudless atmosphere, or radiometric sensors in the millimeter range, in the case of systems operating in adverse weather conditions, in the presence of low clouds, fog, fumes, dust formations, the presence of poor illumination of terrestrial objects – navigation landmarks.

Another prerequisite is the provision of other basic TTRs for autonomous navigation systems for high-speed aircrafts over landmarks. Such requirements include the requirements for the accuracy of positioning of the aircraft and the speed of operation of the CESN, which can be achieved by constructing a system based on the matrix principle, which is now practically feasible in passive radiometric systems.

In the process of creating CENS an important role is played by the development phase of high-speed algorithms for combining images and methods for the synthesis of reference images. The degree of perfection of algorithms and the degree of reliability of the synthesized reference images of navigation objects depends on the probability of correct recognition of objects in the process of CENS operation. At this stage, the technical requirements for the special calculator CENS are also determined.

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Биков В. М. **Модель високоточної системи управління високошвидкісними літальними апаратами** / В. М. Биков, С. М. Биков, О. М. Грічанюк, М. М. Колчигін, В. О. Краюшкін, В. М. Радзіховський, Т. Д. Бережна // Прикладна радіоелектроніка: наук. – техн. журнал. – 2019. – Том 18, № 1, 2. – С. 3–9.

Запропоновано узагальнену модель – структурну схему високоточної системи управління на основі комплексування інерційної навігаційної системи і кореляційно-екстремальної системи навігації високошвидкісних літальних апаратів по наземних об’єктах – орієнтирах. Розглянуто алгоритм функціонування високоточної системи управління.

Проаналізовано основні тактико-технічні вимоги до пасивних радіометричних кореляційно-екстремальних систем міліметрового діапазону, які коректують похибки інерційної навігаційної системи. Показано, що точність визначення взаємних координат високошвидкісних літальних апаратів і наземних об’єктів у результаті застосування систем навігації по зовнішньому поверхневому полю Землі – радіотепловому контрасту, дорівнює одиниці метрів.

Наведено приклади технічної реалізації матричних радіометричних систем міліметрового діапазону, які забезпечують потрібну швидкодію роботи систем порядку частки секунди. Розглянуто тактику застосування високоточної системи управління високошвидкісними літальними апаратами.

Ключові слова: високошвидкісні літальні апарати, високоточна система управління, інерційна навігаційна система, кореляційно-екстремальна система навігації, міліметровий діапазон.

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Предложена обобщенная модель – структурная схема высокоточной системы управления на основе комплексирования инерциальной навигационной системы и корреляционно-экстремальной системы навигации высокоскоростных летательных аппаратов по наземным объектам – ориентирам. Рассмотрен алгоритм функционирования высокоточной системы управления.

Проанализированы основные тактико-технические требования, предъявляемые к пассивным радиометрическим корреляционно-экстремальным системам миллиметрового диапазона, корректирующим ошибки инерциальной навигационной системы. Показано, что точность определения взаимных координат высокоскоростных летательных аппаратов и наземных объектов в результате применения систем навигации по внешнему поверхностному полю Земли – радиотепловому контрасту, составляет единицы метров.

Приведены примеры технической реализации матричных радиометрических систем миллиметрового диапазона, обеспечивающих требуемое быстродействие работы систем порядка долей секунды. Рассмотрена тактика применения высокоточной системы управления высокоскоростными летательными аппаратами.

Ключевые слова: высокоскоростные летательные аппараты, высокоточная система управления, инерциальная навигационная система, корреляционно-экстремальная система навигации, миллиметровый диапазон.

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