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3D MODEL OF LANDMARKS FOR AUTONOMOUS NAVIGATION OF UNMANNED AERIAL VEHICLES

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***Abstract*—*Almost all unmanned aerial vehicles are equipped with inspection earth surface systems that can be used to obtain information about the location of the aircraft using survey-comparative navigation methods. The autonomous determination of unmanned aerial vehicle coordinates with the use of survey-comparative methods of navigation is to finding landmarks whose location is known by their geometric characteristics. Most precisely, the geometric characteristics of 3D object can be obtained using its mathematical model, based on the basic elements of the form. A mathematical model of an object can be represented in the form of two matrices, the elements of which contain information about the shape of the object and the underlying surface, their size and reflective characteristics. The result of determining the location of the unmanned aerial vehicle is the correct solution to the task of recognizing landmarks. In real conditions, it is very difficult to determine the angles of orientation of objects in advance, so it is necessary to apply the mathematical model of the object and determine its characteristics for different orientation angles in relation to the unmanned aerial vehicle. Consequently, the high probability of detecting the landmark is achieved by applying its mathematical 3D model and determining two independent signs of volume and average height for its recognition, it is depending on the angles of its orientation and geometric shape.*

Index Terms—Survey-comparative navigation methods; geometric features; basic elements of the form; mathematical model of the object; the probability of correct solution of the recognition problem.

I. INTRODUCTION

To independently determine their location almost all modern Unmanned Aerial Vehicles (UAVs) use inertial measurement unit (IMU) together with a global positioning system (GPS) that are most expensive and sophisticated on-board equipment (Fig. 1) [1], [2]. However, IMU has accumulative errors and therefore needs constant correction, and the GPS signal strength is rather weak and depends on the presence of artificial and natural obstacles.

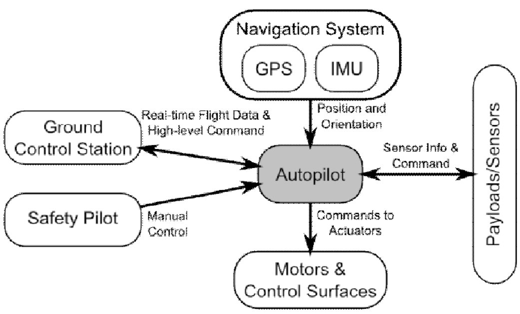

Fig. 1. Unmanned aerial vehicles navigation and control scheme

The main task of modern UAVs is to review the terrestrial surface with the help of systems of technical vision, analysis of information and transmission it to the consumer. Therefore, almost all UAVs are equipped with inspection earth surface systems that can be used to obtain information about the location of the aircraft using survey-comparative navigation methods.

Modern survey-comparative navigation systems provide integral reproduction of a complete set of navigation data, interact with onboard navigators, correct other sensors of navigation information and are the most important information element of the "operator-UAV" system [1].

The essence of survey-comparative methods of navigation is to determine the location of the aircraft by comparing the reference image of the area contained in the memory of the navigation computer with its actual appearance, received with the help of on-board devices of technical vision. If the actual image of the area with the given probability coincides with the reference image of the area the coordinates of which are known, then the coordinates of the aircraft are considered definite.

The navigational content of survey-comparative methods is determined by the type of ground landmarks, their number and the terrain variation. In one-landmark systems, the physical parameters of the real object on the earth's surface are compared with the parameters of the standard landmark, such as the area, geometric form, the radiation spectrum obtaining of which depends on the type of system of the earth's surface inspection. Multi-landmark systems use several landmarks at the same time. In the memory of such systems, information not only about the physical parameters of individual landmarks is stored, but also about the characteristics of their location in relation to each other. The advantage of multi-landmark systems is the large amount of navigational information, small dependence on the loss of some information about the landmarks and the impact of obstacles. However, for the implementation of such systems, it is necessary to have the UAV high-speed electronic computer facilities on board.

Thus, the autonomous determination of UAV coordinates can be carried out by survey-comparative methods of navigation using on-board systems for the inspection of the earth's surface, navigation computer and related software, which allows solving the task of recognizing land-based landmarks.

II. Problem Statement

Sensors of the earth's surface inspection systems, in accordance with the physical characteristics of the signals, are divided into: optical (infrared, television, laser), radiation and radio engineering. The most commonly used in UAVs are optical sensors [4].

Comparative analysis of the sensors (Fig. 2) shows that the maximum amount of information can be obtained from television and 3-D laser sensors, but they have a complicated system for extracting information. Most easily the information can be obtained by infrared sensors, but this information may not be sufficient for survey-comparative navigation methods.

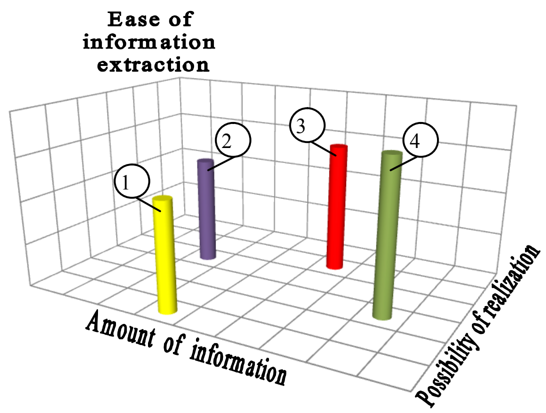

Fig. 2. Comparative of earth observation sensors: *1* is the radar; *2* are infrared sensors; *3* are TV sensors; *4* are 3D laser sensors

So the most complete information about a ground object can be obtained with the help of three-dimensional (3D) laser sensors [5]. The analysis of achievements in the formation of three-dimensional images and the creation on their basis of recognition devices shows that the most promising are laser systems for the formation of 3D images – Light Identification, Detection and Ranging (LIDAR).

LIDAR is a technology for obtaining and processing information about remote objects with the help of active optical systems that use light reflection and its dispersion in transparent and translucent environments [6]. The information on the spatial component in 3D LIDAR is derived from the high accuracy of measuring the propagation time and receiving reflected radiation (Fig. 3).

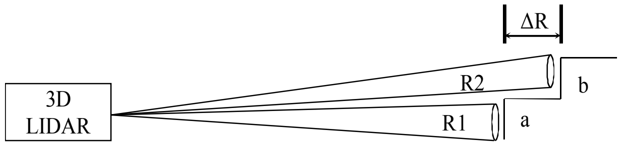

Fig. 3. Method of obtaining 3D image.

The distance difference $\Delta R = R2 - R1$ to the various elements (a; b) of the landmark characterizes the spatial component of the object and is fixed by the time interval τ due to the distance difference to the various elements of the object $\tau = 2\Delta R/c$. The total time of getting reflected from the object radiation is $t + \tau = 2(R + \Delta R)/c$, (where t is the time of radiation propagation to the object, *c* is the rate of propagation of laser radiation).

When receiving reflected from the object radiation on the matrix receiver (MR) of Lidar, the object will have the form of the matrix of time intervals (Figs 4 and 5).

For the solution to the task of recognizing land-based landmarks in modern survey-comparative navigation systems, changes in terrain surface relief are used. Therefore, the main characteristic of the terrain is the height of the surface relief relative to a certain base level.

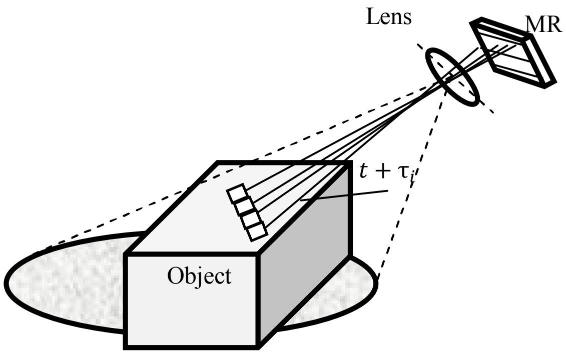

Fig. 4. Scheme for fixing time intervals

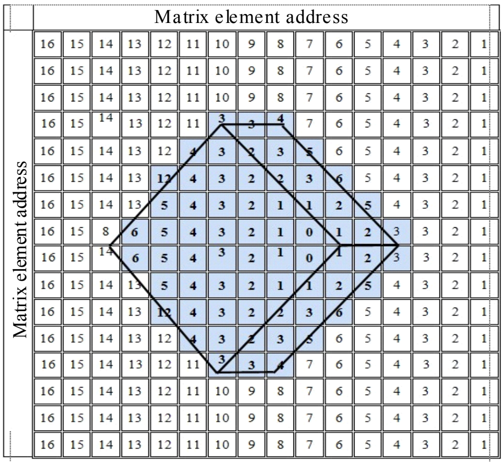

Fig. 5. Scheme for time intervals matrix

However, these characteristics do not fully meet the requirements of the effectiveness of recognition. Therefore, it is necessary to select new ones to accurately describe spatial figures and to be easily obtained from a digital image of the earth's surface. Such characteristics may be 3D geometric features obtained when processing digital images of terrestrial objects using their mathematical models.

III. Problem Solution

When solving the problem of recognition, an important step is the development of a working vocabulary of characteristics. At this stage, the working vocabulary includes only those characteristics of the objects from the entire selected set for recognition, which on the one hand are the most informative, and on the other hand, can be determined by the existing measuring devices or specially created ones. Geometric characteristics are the most appropriate for recognition of terrestrial spatial objects. However, they may differ in amount of information and methods of extraction.

All single terrestrial objects, either natural or created as a result of human activity are material objects and have their size and characteristic form. Despite the large variety of single terrestrial objects, they can be represented with the necessary reliability in the form of simple 3D geometric shapes: parallelepipeds, cylinders, spheres, cones, pyramids, their parts or their combinations (Fig. 6).

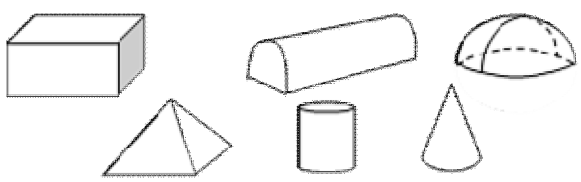

Fig. 6. 3D simple shapes similar to ground objects

A spatial object can be represented as a mathematical model that describes its geometric and reflective characteristics of its surface. The mathematical model of a spatial object consists of a geometric model of an object on the supporting surface, as well as a field model of its reflective characteristics. Creation of a geometric model of a complex object surface and a supporting surface can be reduced to the solution of the approximation problem - finding the function of two variables which least deviates from the given values according to the selected criterion at the reference points [7].

The modeling suggests the use of known methods: parametric representation, nonparametric representation and presentation with the help of basic elements of the form [8], [9].

The implementation of algorithms for constructing images of curvilinear surfaces using the first two methods is very complicated and requires excessive time and resources, so their use is limited. A way of representing the 3D objects using base elements of the form (BEF), which allows quite precisely to construct the surface of the object, simply perform the conversion of the point coordinates of the surface and to calculate the normal to the points of the object surface is more preferred for the description of the 3D objects surfaces. Typically, simple spatial geometric shapes, such as section of plane, are used as a BEF. However, most spatial objects can be described as second-order surfaces or their combinations.

Any surface of the second order is described by the equation of the second degree to the Cartesian rectangular coordinate system. The general second degree equation relative to the variables x, y, z is:

$$a_{11}x_2 + a_{12}y_2 + a_{13}z_2 + a_{14}xy + a_{15}xz + a_{16}yz + a_{17}x + a_{18}y + a_{19}z + a_{110} = 0, \quad (1)$$

The values of the coefficients a_{ij} in the equation (1) determine the shape of the surface (i is the number of the BEF; j is the coefficient number). For example, a plane or surface of the second order.

It is not enough to determine the values of the coefficients a_{ij} to construct a spatial object using surfaces of the second order as BEF. It is necessary to know their size i.e. the maximum and minimum values of the variables x, y, z in equation (1). We will add additional six auxiliary coefficients of size to ten coefficient a_{ij}, which determine the appearance of the surface. Then, for the representation of an object or its part we need information about sixteen coefficients in the model. With the new coefficients, the equation (1) is:

$$a_{11}x_2 + a_{12}y_2 + a_{13}z_2 + a_{14}xy + a_{15}xz + a_{16}yz + a_{17}x + a_{18}y + a_{19}z + a_{110} + a_{111} + a_{112} + a_{113} + a_{114} + a_{115} + a_{116} = 0.$$

The coefficients $a_{11} \ldots a_{110}$ correspond to the coefficients in formula 1 and determine the shape of the surface. The coefficients a_{111} and a_{112} determine the maximum and minimum values of the variable x. In a similar way a_{113} and a_{114} determine for the variable *y*, a_{115} and a_{116} – for the variable *z*.

If the object consists of several BEFs (Fig. 7), then an equation will correspond to each BEF. Then the object can be represented as a matrix of coefficients a_{ij} of size $i \times 6$, where i is the number of BEFs:

$$A = \begin{Vmatrix} a_{11} & a_{12} & \ldots & a_{116} \\ a_{21} & a_{22} & \ldots & a_{216} \\ \ldots & \ldots & \ldots & \ldots \\ a_{i1} & a_{i2} & \ldots & a_{i16} \end{Vmatrix}. \quad (2)$$

This form of information recording is the most convenient for computing and provides compactness and efficiency of access. To determine the coefficients $a_{i1}, \ldots, a_{i10}$, we use the canonical equations of surfaces of the second order, which describe the surface of the irradiated object; it is also necessary to consider the change of coefficients when moving and rotating surfaces of the second order, which are used as BEFs.

The process of the creation of a geometric object model can be divided into three stages. At the first stage, the object is divided into simple geometric figures, each of which can be described by the second order equation and can be represented by a separate basic element of the form (Fig. 7).

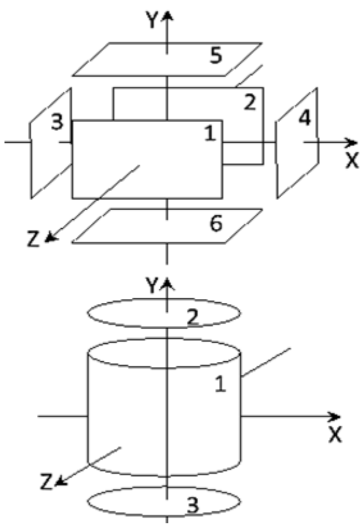

Fig. 7. Basic elements of the form

Each of the selected BEFs is described by the canonical equation of the second order surface, which in general form can be expressed by:

$$\lambda_1 x_i^2 + \lambda_2 y_i^2 + \lambda_3 z_i^2 + d = 0, \quad (3)$$

where λ_1, λ_2, λ_3 are coefficients that determine the type and size of the second order surface.

Then, the angles α_i, β_i, γ_i of the orientation of each BEF are determined, relative to the base coordinate system for which the Earth's motionless spatial coordinate system *XYZ* is chosen. At the second stage, the direct calculation of the coefficients $a_{11}, \ldots, a_{110}$ is performed. To do this, it is necessary to calculate the coefficients of the equations of the second order surfaces for each BEF with the coordinates of the basic coordinate system taking into account the orientation angles and using matrices of the transition between the coordinate systems.

To calculate the coefficients $a_{111}, \ldots, a_{116}$, which determine the size of the BEF relative to the axes *x*, *y*, *z*, it is necessary to use the drawing of the object and its sizes. It should be borne in mind that the size of the BEF is determined in relation to the base coordinate system.

At the third stage, the matrix **A** of coefficients is formed, which can be written into the memory of the computing device in the form of corresponding structural data. Thus, as a result of the above operations, we obtain a model of the spatial object and the supporting surface.

According to the task under consideration, the model of the field of reflecting characteristics of objects can be of different degrees of complexity. The main characteristic of reflection of the surface is the scattering indicatrix $l(\vec{m}; \vec{n})$. It is defined as the ratio of the brightness of the surface of the object in the given direction $L(\vec{m}; \vec{n})$ to the brightness of the ideal scattering L_0 and is written as:

$$l(\vec{m}; \vec{n}) = \frac{L(\vec{m}; \vec{n})}{L_0},$$

where $(\vec{m}; \vec{n})$ are single vectors, which represent the direction of incident and scattered radiation respectively.

Indicators of the scattering of surfaces of natural formations and artificial objects are complex and depend on many factors, which limit the obtaining of the results in analytical form. Therefore, in modeling using energy calculations, the Lambertian reflector model, whose scattering *l* indicating depends not on the direction of incident and scattered radiation, but on the reflection coefficient of the power ρ, is more often used. Thus, the main characteristic of reflection for the model assembly is the reflection coefficient on the power ρ .

In general, some sections of the object and the supporting surfaces have different reflection coefficients, so it is advisable to represent the object in the form of homogeneous areas having the same reflection coefficients. The study of homogeneous areas revealed that these areas coincide with the BEF, especially for surfaces of the first order. Then the model of reflection characteristics can be written in the form of matrix **B**, elements of which are reflection coefficients:

$$\mathbf{B} = \begin{Vmatrix} \rho_1 \\ \rho_2 \\ \dots \\ \rho_i \end{Vmatrix}.$$

Thus, the mathematical model of the object and the supporting surface can be represented as matrices **A** and **B**, elements of which contain information about the shape of the object and the supporting surface, their dimensions and reflective characteristics.

In real life conditions images of three-dimensional objects are exposed to considerable variability depending on the angle of inspection and the position and parameters of sensor. Variation in the angle of inspection and the position of a receiver leads to appearance of different forms and sides of three–dimensional object (Fig. 8).

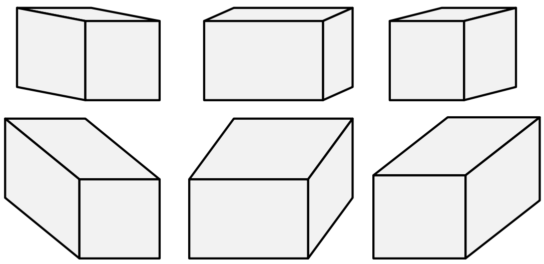

Fig. 8. Variations in landmarks position

When using methods of comparison of standards for recognition, it is necessary to collect a great number of standard images taking into consideration such parameters as the angle of inspection, the angle of the place, and the distance to the landmark that should be recognized. In case all N parameters are considered (n = 1; N) with a K sample of values of every parameter, the necessary number of standard images is to be:

$$\prod_{n=1}^{N} K_n.$$

The comparison of a large number of standard images with the original will take much time and computing resources, which are limited during the UAV flight.

The task of recognition of landmarks by adapted standards suggests known orientation of an object to be recognized in coordinate system X_g, Y_g, Z_g (Fig. 9), which must be common for the object of recognition and the optical system of UAV.

In real life conditions it is very difficult to determine the angles of orientation of the objects beforehand. That is why a mathematical model of the object is necessary for recognition of its characteristics for different angles of the place and the position to UAV. By rotating the object's mathematical model with every set angle it is necessary to synthesize a new image and form its characteristics.

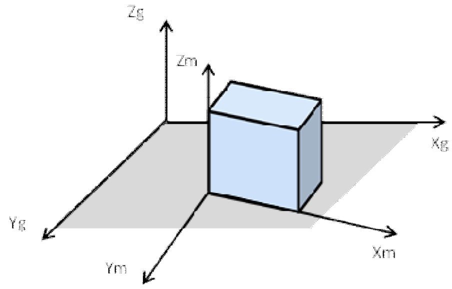

Fig. 9. Position of a terrestrial object in terrestrial coordinate system

The generated series of the object's images as fields of its characteristics is checked by correlations with the analyzed image. Such operations should be carrying out for all types of objects, which are in the field of view the UAV. The global maximum among the fields of all correlation functions indicates the actual position of the object in the field of view, and the corresponding standard landmark indicates it the type and orientation.

The principle of landmark recognition among several objects in case of unknown orientation in shown in Fig. 10.

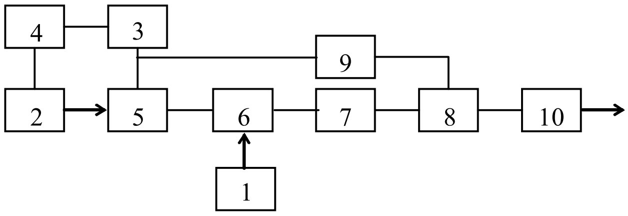

Fig. 10. The scheme of the object recognition according to adaptive standards in condition of unknown orientation of the object

Sensor (LIDAR) 1 forms three-dimensional image of a terrestrial object. In the memory of calculator 2 there are mathematical models of navigation orientations. The systems of UAV determine the terms of the object observation and their position 3, and synchronize these parameters with the initial value of orientation of the mathematical model 4. The model of formation of characteristics 5 synthesizes the image of every standard landmark and forms the field of its characteristics according to the angle of orientation. Analyzer of an image 6 on the basis of detector information 1 forms the characteristics of the terrestrial object and correlates with the field of characteristics of the standards. Correlation functions are analyzed by calculator 7 and in accordance with the results of the analysis processor 8 determines correctness of the recognition. In case of successful recognition of terrestrial landmark, its coordinates are transferred to the control system of UAV 10 and they are simultaneously presented as initial terms of position 9 for further recognition of objects.

IV. RESULT

On the basis of a mathematical model of a spatial object, one can distinguish the following characteristics of the object: size, shape, reflective characteristics. The reflecting characteristics of the object are a variable parameter, which depends on the angles of radiation, weather conditions, and the structure of the object. Therefore, it is inappropriate to use such a characteristic for recognition of landmarks. It is advisable to use the size and shape of the object as signs identifying landmarks for the survey-comparative navigation system of UAV.

The criterion for evaluating the accuracy of the UAV coordinates can be the probability of the correct solution to the task of recognition the navigational landmarks with known coordinates: $\bar{W} = \frac{n_t}{n_\Sigma}$, where n_t is the number of correctly determined landmarks from the whole set of objects; $\bar{W}$ is the total number of experiments to identify landmarks.

So using a model of a spatial object, it is possible to form a certain set of objects with different geometric and reflective characteristics. To perform a navigational task, it is necessary to identify a landmark among these objects.

Geometric features most fully describe a spatial object. Therefore, it is proposed to use the volume V of the object and its average height $\bar{H}$ as a feature. It is expedient to analyze the characteristics using the probability criterion for the correct solution of the recognition problem $\bar{W}$.

The results of the study of the correct decision of the recognition problem, according to the type of features and the distance to the object, showed (Fig. 11) that the probability of detecting landmarks $\bar{W} = 0.7$ and more is achieved at distances up to 3000 m with the simultaneous use of two characteristics of volume V and average height $\bar{H}$.

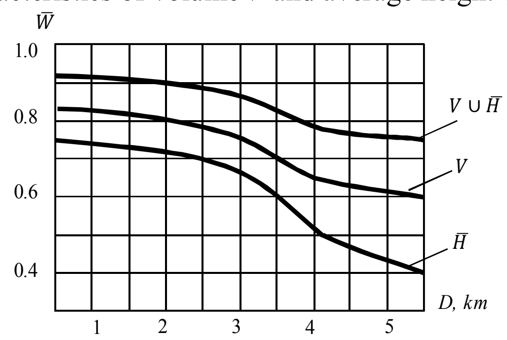

Fig. 11. The correlation between the correct object recognition and the type of characteristics and distance

The probability of the correct solution of the recognition problem $\bar{W} = 0.7$ and more (Fig. 12) is achieved at the orientation angles 70°< χ < 30°and for the objects in the shape of parallelepiped and vertical cylinder.

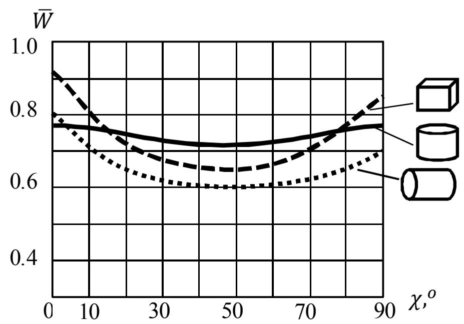

Fig. 12. The correlation between the correct object recognition and the angle of orientation and form

V. CONCLUSIONS

Thus, mathematical modeling of reference landmarks makes it possible to calculate their geometric characteristics and, on their basis, implement survey-comparative navigation methods for determining the location of the UAV.

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О. О. Чужа, Н. В. Пазюра, В. Г. Романенко. 3D модель наземних орієнтирів для автономної навігації безпілотних літальних апаратів

Майже всі безпілотні літальні апарати оснащуються системами огляду земної поверхні, які можна використовувати для отримання інформації про місцеположення літального апарату використовуючи оглядово-порівняльні методи навігації. Автономне визначення координат безпілотного літального апарату із застосуванням оглядово-порівняльних методів навігації полягає у виявленні за геометричними ознаками наземних орієнтирів розташування яких відоме. Найбільш точно геометричні характеристики 3D об'єкта можна отримати за допомогою його математичної моделі на основі базових елементів форми. Математичну модель об'єкта можна представити у вигляді двох матриць, елементи яких уміщують інформацію про форму об'єкта і опорної поверхні, їх розміри та відбивальні характеристики. Результатом визначення розташування безпілотного літального апарату є правильне вирішення задачі розпізнавання наземних орієнтирів. В реальних умовах заздалегідь визначити кути орієнтації орієнтирів дуже складно, тому необхідно застосувати математичну модель об'єкта і визначати його ознаки для різних кутів орієнтації по відношенню до безпілотного літального апарату. Отже висока імовірність виявлення наземного орієнтиру досягається застосуванням його математичної 3D моделі та визначенням для його розпізнавання двох незалежних ознак об'єму та середньої висоти, в залежності від кутів його орієнтації та геометричної форми.

Ключові слова: оглядово-порівняльні методи навігації; геометричні ознаки; базові елементи форми; математична модель об'єкта, імовірність правильного вирішення задачі розпізнавання.

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А. А. Чужа, Н. В. Пазюра, В. Г. Романенко. 3D модель наземных ориентиров для автономной навигации беспилотных летательных аппаратов

Почти все беспилотные летательные аппараты оснащаются системами обзора земной поверхности, которые можно использовать для получения информации о местоположении летательного аппарата используя обзорно-сравнительные методы навигации. Автономное определение координат беспилотного летательного аппарата с применением обзорно-сравнительных методов навигации заключается в выявлении по геометрическим признакам наземных ориентиров расположение которых известно. Наиболее точно геометрические характеристики 3D объекта можно получить с помощью его математической модели на основе базовых элементов формы. Математическая модель объекта может быть представлена в виде двух матриц, элементы которых вмещают информацию о форме объекта и опорной поверхности, их размеры и отражающие характеристики. Результатом определения расположения беспилотного летательного аппарата является правильное решение задачи распознавания наземных ориентиров. В реальных условиях заранее определить углы ориентации ориентиров очень сложно, поэтому необходимо применить математическую модель объекта и определять его признаки для различных углов ориентации по отношению к беспилотному летательному аппарату. Итак, высокая вероятность обнаружения наземного ориентира достигается применением его математической 3D модели и определения для его распознавания двух независимых признаков объема и средней высоты, в зависимости от углов его ориентации и геометрической формы.

Ключевые слова: обзорно-сравнительные методы навигации; геометрические признаки; базовые элементы формы; математическая модель объекта, вероятность правильного решения задачи распознавания.

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