THEORY AND METHODS OF SIGNAL PROCESSING

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[1]O. O. Chuzha,
[2]V. G. Romanenko

DIFFERENTIAL ANALYSIS OF 3D SENSOR IMAGES OF SURVEY-COMPARATIVE NAVIGATION SYSTEMS

[1,2]Educational&Research Institute of Air Navigation, Electronics and Telecommunications,
National Aviation University, Kyiv, Ukraine
E-mails: [1]achuzha@nau.edu.ua, [2]sttt912@yahoo.com

Abstract*—Survey-comparative navigation systems are used for identification of landmarks that typically in the form of spatial objects the underlying surface. The most obvious method for obtains geometric features of the spatial object is processing its three-dimensional (3D) image. For processing 3D images of the spatial objects in the form of a matrix of time intervals, it is proposed to use a differential method based on the application of the properties of the first and second of derivatives of functions. The differential method processing 3D images allows implementing algorithms for determining the boundaries of the object on the background of the underlying surface, to determine the basic elements of the form of the object, their number and proportions.*

Index Terms—Survey-comparative navigation methods; LIDAR; cross lines; envelope of time intervals; basic elements of the form; derivative of a function; differential method of analysis.

I. INTRODUCTION

The principal purpose of the 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 form, received with the help of on-board devices of technical vision [1], [2]. 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 image of the terrain contains a lot of quantity of information, the processing of which increases the time determination of the location of the aircraft, so it is advisable to compare not the image of the area, but clearly expressed landmarks on it (Fig. 1).

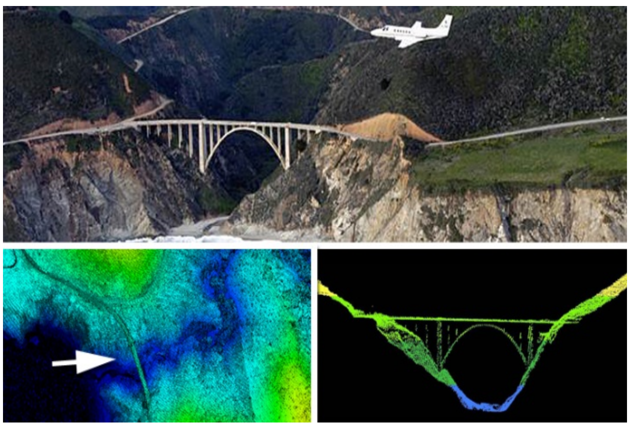


Fig. 1. The landmarks on image of the terrain

The using of the survey-comparative navigation system (SCNS) suggests finding of objects on the plot of the earth's surface similar to the reference landmarks. It means necessary to solve the problem of recognition of terrestrial objects [3].

There are passive and active sensors for creating 3D images of the spatial objects. Passive sensors are systems that use a variety of stereoscopic methods for image processing. Active sensors include distance-measuring systems and systems that use the holographic methods. The use in airplanes of passive sensors of SCNS for to obtain 3D images of remote objects and their automatic processing is problematic, as to increase the resolution of the range it is necessary to increase the geometric basis of observation. It is problematic to use SCNS that based on holographic methods, which is related to the requirements for a laser source, the main of which is to ensure the coherence of radiation in time and space.

Distance-measuring systems creating 3D images of the spatial objects by their irradiating with a laser beam, while fixing their geometric characteristics and distance to them.

The analysis of achievements in the formation of 3D images and the creation on their basis of recognition devices shows that the most promising are the distance-measuring laser systems of formation of 3D images which have name the LIDAR (Light Identification, Detection and Ranging) [4].

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 [5].

To solve the problem of recognizing of spatial objects, it is necessary to identify the features that can be determined based on the processing of their 3D images and characterize the objects to be recognized the most fully. The features used for recognition are divided into deterministic, probabilistic, logical and structural. The analysis of features of spatial objects carried out by the informative criterion has shown that the most informative features that do not depend on the type of sensor are geometric features (size, area, shape, volume, etc.). In that way, for determine the geometric features of a spatial object on the earth's surface, it is necessary to perform an analysis of its 3D image is formed by the LIDAR.

II. Problem Statement

The information on the spatial component in the 3D LIDAR is derived from the high accuracy of measuring the propagation time and receiving radiation reflected from different elements of the object (Fig. 2).

The distance difference 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. Overall time of reflections from the object of radiation is $t+\tau = 2\left(R+\Delta R\right)/c$, (where t is the time of radiation propagation to the object; c is the rate of propagation of laser radiation).

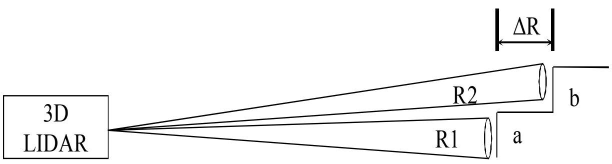


Fig. 2. Method of obtaining the 3D image

When receiving reflected from the object radiation on the matrix receiver (MR) of the LIDAR, the object will have the form of the time interval matrix (Figs 3 and 4).

The information contained in 3D image of an object can be used to recognize it. When processing the 3D image, the same features can be obtained as in the case of 2D image (area, dimensions). In addition, the processing of the 3D image allows obtaining additional features of the object (shape, volume, etc.).

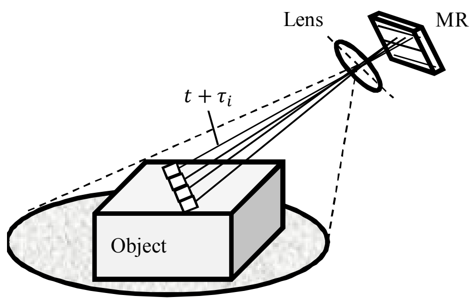


Fig. 3. Scheme for fixing time intervals

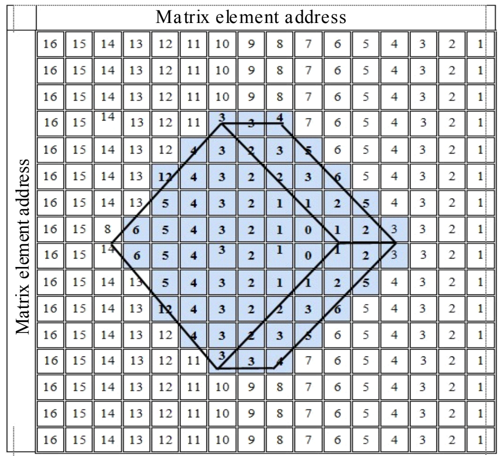


Fig. 4. Scheme for the time interval matrix

An analysis of the geometric features of a spatial object has shown that volume is the most complete characteristic of a spatial geometric figure, which can be determined by processing its 3D image.

Because of this, for the implementation of the survey-comparative navigation method, model of 3D image analysis of the LIDAR system should be used. That will allow defining geometric features of spatial objects necessary for solving the task of recognition and identification of landmarks.

III. Problem Solution

While researching a 3D image of a spatial object a more sophisticated analysis of the model of formation of the time interval matrix is needed.

The time intervals $\tau_{i,j}$ measured by the LIDAR consist of two components (Fig. 5):

– t_0 is the time that characterizes the distance R from the plane of the receiving lens of the LIDAR to the tangential plane perpendicular to the direction of radiation propagation and it is crossing the object of observation at the nearest point to the LIDAR. This time characterizes the range to the object;

– $\tau_n(i,j)$ is the time that characterizes the distance from the tangent plane to the nth point on the object containing the projection of the ith element of the j-line of the receiver of radiation. This time is a spatial characteristic of the object.

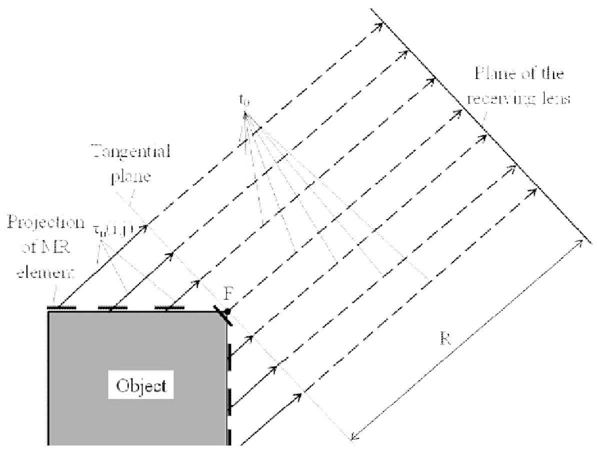


Fig. 5. The model for the formation of a time intervals

Therefore, the LIDAR will form the time interval matrix of the object of observation in the form of time intervals of its spatial characteristics without taking into account the distance to the object:

$$\tau_n(i,j) = \left(\tau_{i,j} - t_0\right) + \Delta\tau_{i,j},$$

where $\Delta\tau_{i,j}$ is the quantity characterizing the measuring error of the time interval.

Defining the geometric features of an object by using its 3D image requires it is defining of the boundaries of the object and its form. To accomplish this task, a differential method based on usage of the geometric characteristics of the derivative function can be used.

The derivative of a function $y = f(x)$ of a variable x is a measure of the rate at which the value y of the function changes with respect to the change of the variable x [6]. It is called the derivative of f with respect to x. If x and y are real numbers, and if the graph of f is plotted against x, the derivative is the slope of this graph at each point [3]. If y is a linear function of x, meaning that the graph of y is a line (Fig. 6a), then in this case, $y = f(x) = mx + b$, for real numbers m and b, and the slope m is given by

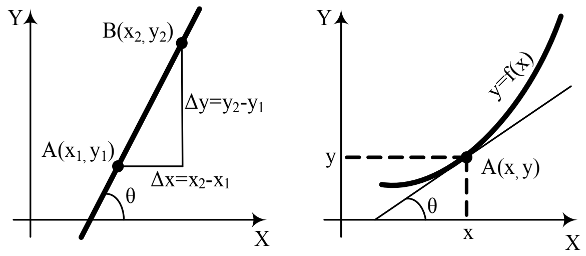
$$m = \frac{\Delta y}{\Delta x} = \mathrm{tg}\,\theta.$$

This gives an exact value for the slope of a line. Sometimes the coefficient m is called the slope or the angular coefficient. If the function f is not linear, however, then the change in y divided by the change in x varies: differentiation is a method to find an exact value for this rate of change at any given value of x, this change determines the curvature of the function (Fig. 6b).

The geometric meaning of the derivative $f'(x)$ of the function $f(x)$ at the point A (x, y) is the angular coefficient of the tangent to the graph of the function $y = f(x)$ (Fig. 6). The equation of a line on a plane is written by

$$y = mx + b,$$

where $m = \mathrm{tg}\,\theta = f'(x)$ is the angular coefficient of the tangent (slope).



(a) (b)

Fig. 6. Slope of a linear function (a) and the tangent line at $A(x, y)$ (b)

For the application of the differential method in the processing of 3D images, analyzing the cross-section of the ground object by the plane that passes through the horizontal line of elements of the MR and coincides with the direction of radiation propagation (Fig. 7).

This plane crosses an object and forms intersection lines (straight or curved) with its surfaces, which are functions, to which one can construct tangents, and determine their slope at different points. These points are the projections of the elements of the MR on the irradiated object.

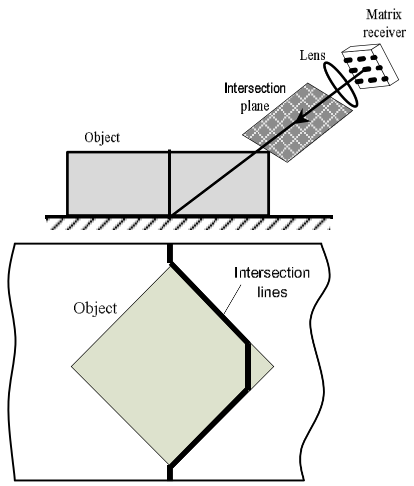


Fig. 7. The cross-section of the spatial object by the plane

Any spatial object can be described using basic elements of the form (BEF), that is, simple geometric figures [7], [8]. The basic elements of the form that create a spatial object may have the form of a plane or surface of the second order (cylinder, hemisphere, etc.) [9]. Depending on the type of surface of spatial object (its basic elements of the form), its intersection lines have different forms and different derivatives of their functions:

a) at the irradiation of the plane, its intersection line is a straight line, and the derivative of this function is a constant slope (Fig. 8a);

b) if the object consists of several planes, which are placed at different angles in relation to the direction to the MR, then each plane to have another constant slope (Fig. 8b);

c) when irradiated surfaces of the second order, the intersection lines are curves, and the derivatives of these functions at each point will constantly change (Fig. 8c).

The matrix receiver of radiation registers the image of the object, so it is reasonable to carry out an analysis of images in series using time intervals, registered by separate elements of the MR.

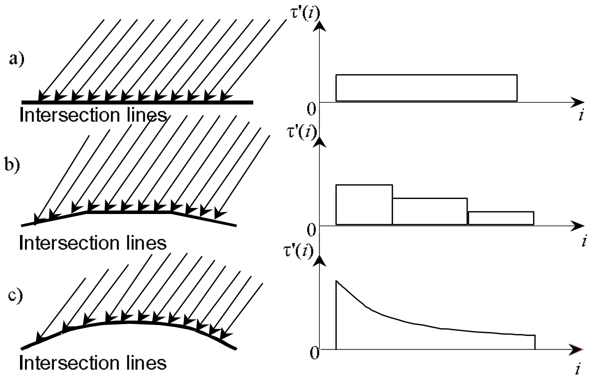


Fig. 8. The forms of intersection lines and their derivatives of functions

In this case, we assume that the elements of the horizontal line of the MR are on the OX axis and the function $y = f(x)$ represents the enveloping of time intervals $\tau(i)$, which are registered by the elements of the horizontal MR line (Figs 9 and 10c), as a result we have expression:

$$\tau_n(i) = f_n(i),$$

here $\tau_n(i)$ is the function of the enveloping of time intervals for the nth BEF; i is the index number of element on the line of MR.

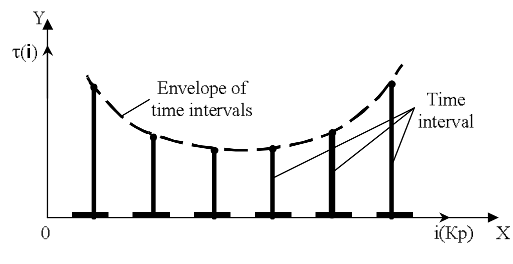


Fig. 9. Envelope of time intervals: Kp is the relative distance between elements on the MR line

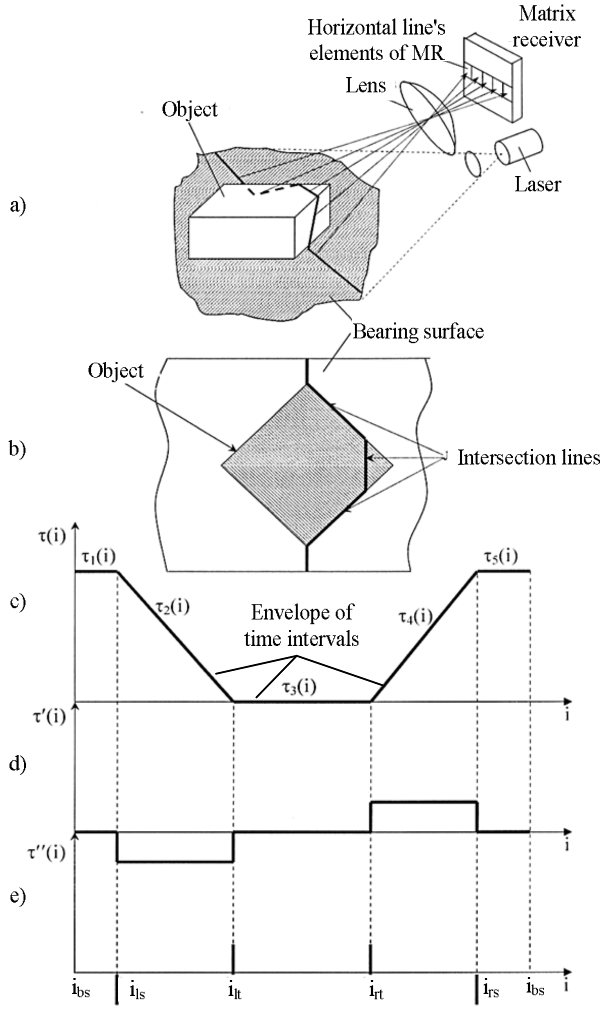


Fig. 10. Analysis of the 3D image of a "parallelepiped" type object using the differential method

When irradiating a ground object consisting of basic elements in the form of a plane, the enveloping of time intervals for one horizontal line of the MR will have the form shown on Fig. 10c.

This case can be described mathematically using the system of equations:

$$\begin{cases} \tau_1(i) = m_1 i + b_1, & [i_{bs}; i_{ls}], \\ \tau_2(i) = m_2 i + b_2, & [i_{ls}; i_{lt}], \\ \tau_3(i) = m_3 i + b_3, & [i_{lt}; i_{rt}], \\ \tau_4(i) = m_4 i + b_4, & [i_{rt}; i_{rs}], \\ \tau_5(i) = m_5 i + b_5, & [i_{rs}; i_{bs}]. \end{cases}$$

here i_{bs} is the index number of element on the line of MR, which fix the bearing surface; i_{ls} is the index number of element on the line of MR, which fix the left side of the object; i_{rs} is the index number of element on the line of MR, which fix the right side of the object; i_{lt} is the index number of element on the line of MR, which fix the left top side of the base of the object; $i_{rt}$is the index number of element on the line of MR, which fix the right top side of the base of the object; m_n is the slope for the nth BEF; b_n is the coefficient for the nth BEF.

Each equation of the system corresponds to describing intersection line, which is created by the intersection plane with nth BEF. Therefore, the coefficients of the equations $m_1 - m_5$ characterize the slope between the horizontal line of elements of the MR and the corresponding intersection line of the nth BEF. Proceeding from this, using the slope, that is, the derivative of the function, one can characterize the planes from which the irradiated object forms. In the case described, the derivative of the time intervals obtained by each individual element of the MR line are written by:

$$\tau_n'(i) = \frac{d\tau_n(i)}{dK_\partial} = m_n,$$

here $\tau_n'(i)$ is the derivative of the enveloping of time intervals $\tau(i)$ for the n-th BEF of the ith element of the MHI line.

Assuming that all elements of the horizontal line of the MR are located at the same distance from each other, that is $dK_p = \text{const}$, then the main characteristic of the planes from which the object is composed is the difference between the time intervals fixed by adjacent elements for each j-line of the MR:

$$d\tau(i) = \tau(i+1) - \tau(i)\,.$$

For each BEF, of which the irradiated object is composed, the calculation of derivatives of the enveloping of time intervals for one MR line is written as follows:

$$\begin{cases} \tau_1'(i) = m_1 = 0,\ (\theta = 0), & [i_{\text{bs}}; i_{\text{ls}}], \\ \tau_2'(i) = m_2, & [i_{\text{ls}}; i_{\text{lt}}], \\ \tau_3'(i) = m_3 = 0,\ (\theta = 0), & [i_{\text{lt}}; i_{\text{rt}}], \\ \tau_4'(i) = m_4, & [i_{\text{rt}}; i_{\text{rs}}], \\ \tau_5'(i) = m_5 = 0, (\theta = 0), & [i_{\text{rs}}; i_{\text{bs}}]. \end{cases}$$

The derivative functions: $\tau_1'(i)$, $\tau_3'(i)$, $\tau_5'(i)$ are zero, because the intersection lines for each BEF in the example are parallel to the line of the elements of the MR, which is the angle between them is zero $(\theta = 0)$, therefore:

$$\text{tg}(0°) = 0 = m_n = \tau_n'(i)$$

An analysis of the first derivative of the envelope of time intervals in the case described is shown in Fig. 10d.

Thus, the analysis of a 3D image using the first derivative functions of the enveloping time intervals makes it possible to determine the shape and orientation of the main components of the spatial object.

To determine the geometric features of objects it is necessary to have their actual size. If the distance to the object and the vision angle of one element of the MR is known, then it is possible to determine the size of its projection on the irradiated surface, and if the number of elements of the MR, that received the image of the object is known then can be determined its geometric dimensions. Therefore, it is necessary to determine the number of MR elements that received the image of each BEF of object and their boundaries.

The physical content of the first derivative of the function is the rate of change in the measured value. In our case, this is the rate of change in the time of arrival the laser radiation reflected from the elements of the object.

The physical content of the second derivative is the rate of change in speed, that is, acceleration. In the case of analysis of time intervals, the second derivative will provide information about the rate of change of slopes, that is, the points of transition between the BEF of the object. These transition points or the numbers of the elements of the MR, it will allow to determine the geometric dimensions of the object. In addition, if known the information about the distance and the angle of the place of the object, then can be to determine its height and volume.

Determine the boundaries of the BEFs of the object are difficult, because in some cases the transition from one element of the surface of the object to the second is not clearly expressed. For a clearer separation of the boundaries of the BEFs, an analysis of the change of time intervals using the second derivative can be used. For the case of analysis of the 3D image of a "parallelepiped" type object discussed in Fig. 10 the result of using the second derivative will be the transformation of the boundaries of the object elements into more expressive single values (Fig. 10e), which can be written as:

$$\begin{cases} \tau_1''(i) = 0, \\ \tau_{12}''(i) = m_2 - m_1, & [i_{ls}], \\ \tau_2''(i) = 0, \\ \tau_{23}''(i) = m_3 - m_2, & [i_{lt}], \\ \tau_3''(i) = 0, \\ \tau_{34}''(i) = m_4 - m_3, & [i_{rt}], \\ \tau_4''(i) = 0, \\ \tau_{45}''(i) = m_5 - m_4, & [i_{rs}], \\ \tau_5''(i) = 0. \end{cases}$$

here $\tau''_n(i)$ is the second derivative of the enveloping of time intervals for the *n*th BEF of the *i*th element of the MHI line.

The analysis of the second derivative of time intervals clearly distinguishes elements on the line of MR, which determine the boundaries of the object's BEFs. After determining the numbers of these elements for each horizontal line of the MR, can be found the total number of elements of the MR on which the BEFs of the object is projected, which will allow to more accurately determine its the geometric features: height and volume.

IV. Results

The use of the differential method for treating 3D images as a matrix of time intervals was performed for a "parallelepiped" object with 12×12×27-meter dimensions (Fig. 11).

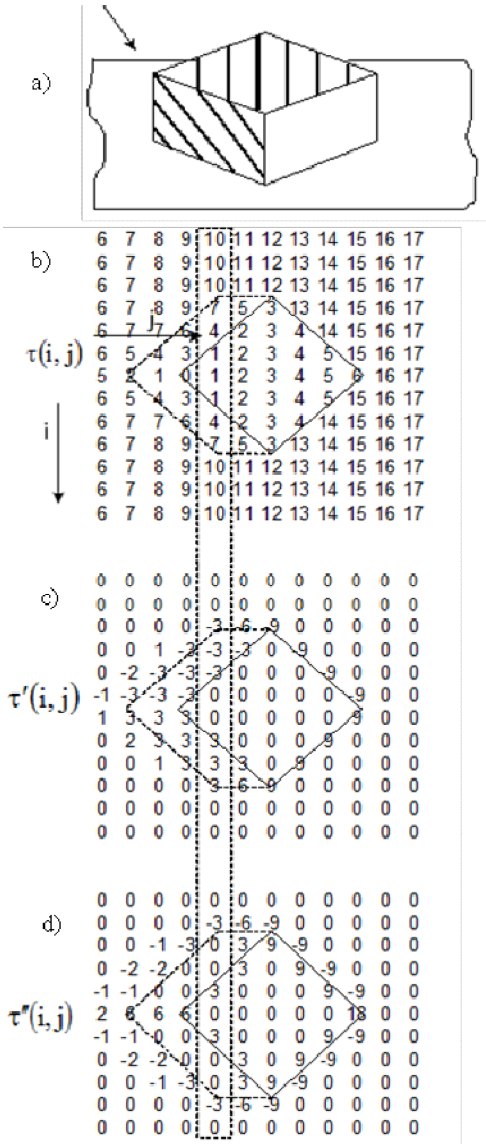


Fig. 11. The use of the differential method for analysis a "parallelepiped" object with 12×12×27-meter dimensions

Results of researches show that the analysis of the first derivative of the time intervals may select the object on the bearing surface and determine its shape (Fig. 11c). Together with the second derivative that may determine the boundaries of the basic elements of the shape of the object (Fig. 11d) and taking into account the characteristics received by the LIDAR and distances, its geometric features can be calculated.

V. Conclusions

Using the differential method for analysis of 3D images of objects allows determining their sizes, shape and therefore to form their geometric features. Applying these features and recognition algorithms, it will allow determining the location of the aircraft using survey-comparative navigation tools.

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Oleksii Chuzha. Candidate of Science (Engineering). Associate Professor.
Avionics Department, Educational and Scientific Institute of Air Navigation, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Institute of Military Air Force, Kyiv, Ukraine, (1988).
Research area: Operation of aviation automated systems.
Publications: more than a forty.
E-mail: achuzha@nau.edu.ua

Romanenko Viktor. Candidate of Science (Engineering). Associate Professor.
Avionics Department, Education & Research Institute of Air Navigation, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Civil Aviation Engineers Institute, Kyiv, Ukraine, (1988).
Research interests: cavitation in liquid systems and optoelectronics.
Publications: 64.
E-mail: rvg11235@ukr.net

О. О. Чужа, В. Г. Романенко. Диференціальний аналіз зображень 3D датчиків оглядово-порівняльних навігаційних систем

Оглядово-порівняльні навігаційні системи використовуються для виявлення орієнтирів, які зазвичай мають вигляд просторових об'єктів на підстилаючій поверхні. Найбільш очевидним способом отримання геометричних ознак просторового об'єкта є обробка його тривимірного (3D) зображення. Для обробки 3D-зображень просторових об'єктів у формі матриці часових інтервалів пропонується використовувати диференціальний метод, що базується на застосуванні властивостей першої та другої похідних функцій. Диференційований метод обробки 3D-зображень дозволяє реалізувати алгоритми визначення меж об'єкта на фоні підстилаючої поверхні, його базових елементів форми, їх кількість та розміри.

Ключові слова: оглядово-порівняльні методи навігації; LIDAR; лінії перетину; огинаюча часових проміжків; базові елементи форми; похідна функції; диференціальний метод аналізу.

Чужа Олексій Олександрович. Кандидат технічних наук. Доцент.
Кафедра авіоніки, Навчально-науковий інститут аеронавігації, Національний авіаційний університет, Київ, Україна.
Освіта: Київський інститут Військово-повітряних Сил, Київ, Україна, (1988).
Напрям наукової діяльності: експлуатація авіаційних автоматизованих систем.
Кількість публікацій: понад сорок.
E-mail: achuzha@nau.edu.ua

Романенко Віктор Григорович. Кандидат технічних наук. Доцент.
Кафедра авіоніки, Навчально-науковий інститут аеронавігації, Національний авіаційний університет, Київ, Україна.
Освіта: Київський інститут інженерів цивільної авіації, Київ, Україна, (1988).
Кількість публікацій: 64.
E-mail: rvg11235@ukr.net

А. А. Чужа, В. Г. Романенко. Дифференциальный анализ изображений 3D датчиков обзорно-сравнительных навигационных систем

Обзорно-сравнительные навигационные системы используются для выявления ориентиров, которые обычно имеют вид пространственных объектов на подстилающей поверхности. Наиболее очевидным способом получения геометрических признаков пространственного объекта является обработка его трехмерного (3D) изображения. Для обработки 3D-изображений пространственных объектов в форме матрицы временных интервалов предлагается использовать дифференциальный метод, основанный на применении свойств первой и второй производных функций. Дифференцированный метод обработки 3D-изображений позволяет реализовать алгоритмы определения границ объекта на фоне подстилающей поверхности, его базовых элементов формы, их количество и размеры.

Ключевые слова: обзорно-сравнительные методы навигации; LIDAR; линии пересечения; огибающая временных интервалов; базовые элементы формы; производная функции; дифференциальный метод анализа.

Чужая Алексей Александрович. Кандидат технических наук. Доцент**.**
Кафедра авионики, Учебно-научный институт аэронавигации, Национальный авиационный университет, Киев, Украина.
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Направление научной деятельности: эксплуатация авиационных автоматизированных систем.
Количество публикаций: более сорока.
E-mail: achuzha@nau.edu.ua

Романенко Виктор Григорьевич. Кандидат технических наук. Доцент.
Кафедра авионики, Учебно-научный институт аэронавигации, Национальный авиационный университет, Киев, Украина.
Образование: Киевский институт инженеров гражданской авиации, Киев, Украина (1988).
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E-mail: rvg11235@ukr.net