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Depth map generation for mobile navigation systems based on objects localization in images

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ABSTRACT

This paper is aimed to develop a method for a depth map generation based on objects localization in images, obtained through a stereopair. The proposed solution describes the objects by the following informative elements: contours, interest points (points of the greatest curvature of the contour), center of mass of the object. Moreover, to describe the contour of the image, it is proposed to use methods with adjustable detailing, based on the wavelet transform, which has frequency-selective properties. The novelty of this method is the possibility of obtaining an approximate depth map by simplifying the calculation of stereo image difference values, which is traditionally used to generate a depth map. Software was developed based on the proposed solutions. Modeling confirmed the effectiveness of the proposed approach. The proposed method makes it possible to significantly reduce the number of computational operations and, consequently, improve depth map generation performance and recommend the proposed method for mobile navigation systems operating in conditions of limited computing and energy resources. The method provides object detection and spatial positioning, makes it possible to obtain reliable information about the distance to objects for other subsystems that use technical vision in their operation, for example, navigation systems for visually impaired people, robotic devices, etc.

Keywords: Mobile navigation systems; depth map; selection of contours; localization of objects in the image; wavelet transform

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1. INTRODUCTION

The rapid growth of technical facilities performance and the emergence of open-source software libraries for the implementation of computer vision, have led to an avalanche-like growth of applications that allow solving a wide range of problems in almost all areas of human activity. For example, we can single out the task of 3D-probing, the purpose of which is to get information about the features of the location of objects and estimate the depth of the scene, understanding the geometry of three-dimensional objects [1]. Such tasks are solved in Internet of Things systems, logistics, robotics, in various mobile navigation systems, including those for people with visual impairments [2, 3]. It should be noted that systems with 3D-probing allow solving object recognition problems at a higher quality level compared with 2D systems, due to the presence in the image of information not only about the brightness and color, but also about the depth of the image. However, recognition of 3D objects is still a difficult task compared to 2D recognition, especially for systems built on low-power processors for the Internet of Things and mobile navigation systems. In this case, along with the classic algorithmic problems inherent in mobile navigation systems (the lack of large sets of labeled real data and the complexity of their labeling), developers are faced with time, energy, and computing restrictions for the key algorithms for recognition and understanding scenes with three-dimensional objects [4, 5]. The algorithm of generation a depth map, considering resource constraints, is an urgent task, which is solved in this paper.

2. RELATED WORK

Today, a few technologies are used to obtain a depth map [6, 7]. Let`s have a look at some conventional ones. One of the modern and common technologies is based on the so-called three-dimensional Time-of-Flight systems (three-dimensional ToF systems). The idea of the technology is straightforward: ToF-camera measures the distance by actively illuminating the object with infrared light invisible to the human eye, then reads the time it takes to reflect from the object and determines the distance to the object from it. Time-of-flight cameras can be used in modern smartphones and allows setting up and simplifying the video shooting mode, adding high-quality special effects. However, they are still quite resource-intensive and, with high accuracy requirements, are difficult to use for mobile systems [7].

The next approach used to build a depth map is based on the structured illumination method, which works on the principle of projecting points (or more often lines) onto a known reference sample and onto an object. The 3D object distorts the reference sample, and the 2D camera captures this distortion [8]. According to the degree of the resulting distortion in comparison with the reference one, a depth map is calculated. This method is used with stereoscopic systems. The advantage of this method is the ability to achieve very high spatial resolution and very high accuracy at close distances. The main disadvantage of the method is the limitation of depth measurement to two meters, which is due to the fact, that the distortion of the pattern may not be distinguishable if the light source is located nearby. In addition, the method is characterized by a loss of accuracy on dynamic objects due to the analysis of several projections.

The third classic and most well-known solution is a simpler technology in relation to ToF and the structured lighting method – a system based on stereoscopic vision. To implement this plotting and depth estimation solution, at least two video cameras separated by a certain distance are required. Like the human eye, a given reference point in space will be at different positions in each camera, allowing the system to calculate the position of that point in space. The algorithm for constructing a depth map measures the offset along the x-axis of each point of the right frame and the correlation corresponding to the same point of the left frame [9, 10]. The search for the corresponding point occurs strictly along the line of the horizontal strobe of each frame, therefore, in order to correctly determine the distance to objects during vertical calibration (y-axis in the image), the position of the cameras is set so that the horizontal lines of both cameras coincide. Horizontal calibration (x-axis in the image) is performed by rotating the cameras relative to each other by such an angle when the coordinates of the points along the x-axis at distance more 10 meters coincide. In other words, this method requires camera positioning with pixel accuracy both horizontally and vertically, which is problematic and could reduce the quality of object positioning [11, 12].

Thus, stereoscopic systems have a big advantage – they are cheaper, since they do not require such expensive hardware as ToF systems and active lighting systems. Also, they are simpler in technical implementation. It should be noted that another argument in favor of using stereoscopic systems in mobile systems is the availability in the OpenCV library of numerous open-source general-purpose algorithms for implementing stereo vision in different programming languages [9].

The main disadvantages of stereoscopic systems for generating the depth map for mobile navigation systems are following [11, 12]:

– the necessity of cameras calibration – even with pixel-perfect positioning of cameras, obtaining a depth map in mobile navigation systems (for example, when avoiding obstacles) causes difficulties with the need for pixel-by-pixel correlation of images;

– the result is heavily relying on the quality of the original images and camera parameters, lighting and illumination of each of the cameras;

– the number of computational operations and, consequently, performance is based on the size and quality of the image.

One of the ways to reduce these disadvantages is using an information from the process of objects contour selection, since the contours are not only the most informationally significant part of objects, but this approach can significantly reduce the number of computational operations [13]. However, in this case the quality of the depth map depends on the efficiency of the applied contour detection methods which leads to sophistication of the depth map generation algorithms.

In this paper, we propose a depth map generation method for mobile navigation systems. The proposed method is using information of objects localization in images and could work under heavy time, energy, and computational power restrictions.

3. METHOD FOR GENERATING A DEPTH MAP WITH THE HELP OF OBJECTS LOCALIZATION INFORMATION

The proposed method uses difference values calculated between two localized objects in two photo or video images. Information of objects

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localization is calculated with the help of given, optical-geometric parameters of objects. This information used for objects selection against the background with the other objects [14, 15]. The localization of objects is described by the following informative elements: contours, characteristic points (points of the greatest curvature of the contour) or the center of mass of the object.

1. Description of object localization by contour

The most informationally significant part of objects is their contours. As noted above, the transition from a raster representation of an image to a contour image reduces the amount of information processed by 2-4 orders of magnitude, provides invariance to brightness transformations, and, therefore, increases the efficiency of depth mapping.

Most edge detection methods can be described by a two-step algorithm [14, 15]:

– in the first step, the energy of the images of objects is concentrated near the intensity drops (underlining the contours);

– in the second step, contour points are selected.

When emphasizing the contours, it is considered that for the reproduction and presentation of points, lines and small details in the image, high frequencies, especially in the region of 0.2 – 0.5 sampling frequencies, are decisive. However, the selection of high-frequency components, although it improves the localization of the details of objects, enhances the noise.

It should be noted that since the analyzed image is most often locally heterogeneous, it is expedient to carry out localization at different levels of detail. For some real-world tasks, to generate a depth map, it is enough to select the outer contour of an object (silhouette), for other tasks, small details of the object are important.

Thus, in order to localize an object in an image, it is advisable to apply a transformation that has the property of spatial-frequency localization [16, 17]. This requirement is satisfied by real wavelets in the form of odd symmetric functions with a compact or effective carrier, for example, such wavelets as: Haar, Gauss, based on the split Gaussian basis function (GBF), bounded sine wavelet, hyperbolic WP basis functions (HWT), etc. These functions can be used as basic functions, since they satisfy the necessary requirements (localization, admissibility, oscillation, and boundedness).

These wavelet functions are characterized by similar frequency-selective properties, in other words the frequency value at the extremum point for all functions is determined by the dependence [17]

$$\omega_{extr} = \frac{k}{s},$$

where: k – constant value, which is determined by the type of the basis wavelet function; s – scale level.

The frequency value at the extremum point for different types of basis functions at the same scale level s is different and considering when choosing a basis for highlighting the structural features of an image with different levels of detail [15]. This is confirmed by the results of modeling the wavelet transform of the test image lines (Fig. 1a and Fig. 1b). At s=1, small and large image details as a result of processing in the intensity drop region have equal maxima (Fig. 1c). As the scale increases, the relative sizes of small detail peaks decrease (Fig. 1d), and at the same time, the amplitude increases peak at the boundaries of large-scale object details.

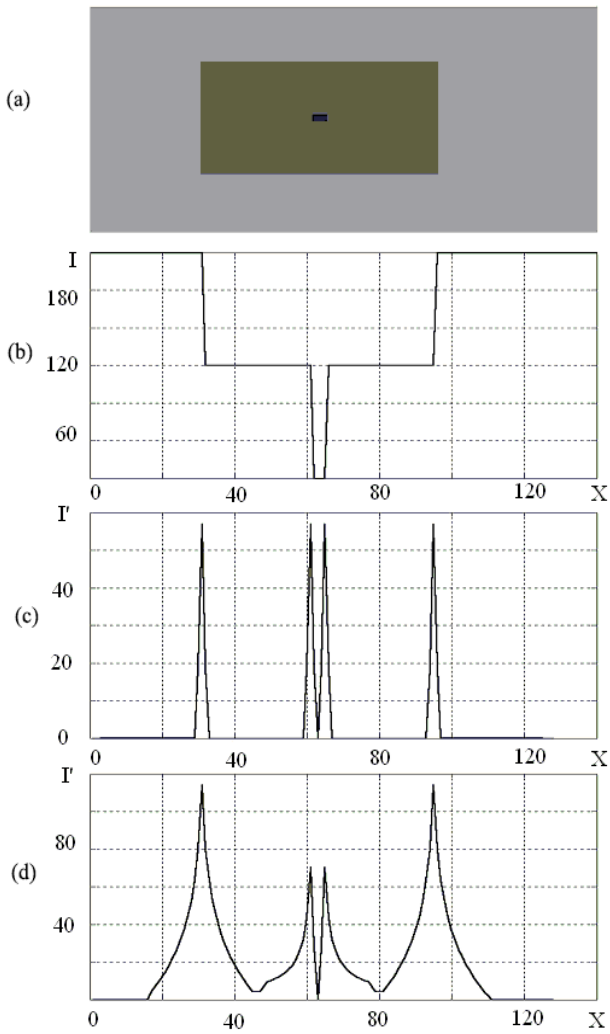

Fig. 1. **Modeling results:**
(a), (b) – test image and its line;
(c), (d) – image line in the wavelet transform domain for Gauss Wavelet Transform on different scales $s_2 > s_1$
***Source:* compiled by [15]**

The position of the maximum of the amplitude-frequency characteristic of the wavelet transform reflects well its frequency-selective properties on different scales [15, 17] (Fig. 2). Thus, by changing the scale, it is possible to adjust the detail of the image of the object, to use only the contour (as structural elements) of large objects when generation a depth map.

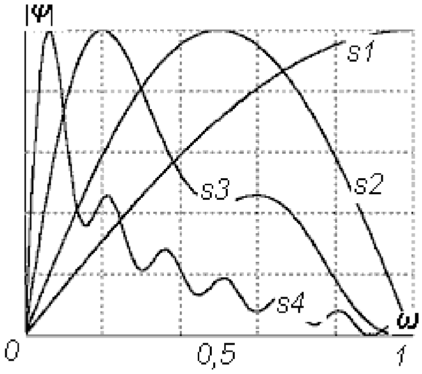

Fig. 2. **The amplitude-frequency characteristic of the GWT at different scales s ($s_4 > s_3 > s_2 > s_1$)**
Source: **compiled by [15]**

2. Description of object localization by characteristic points

Characteristic points (CP) are the most informative part of the contour [14, 15]. The main algorithmic apparatus used in the selection of CP is the analysis of the contour curvature function:

$$k(S_j) = F(S_j) - F(S_{j-1}),$$
$$F(S_j) = arctg\left[\frac{y(S_j) - y(S_{j-1})}{x(S_j) - x(S_{j-1})}\right],$$

where: S_j – length of the contour curve at point *j*; $x(S_j), y(S_j)$ – coordinates of the *j*-th contour point.

The extrema of the curvature function determines the characteristic points. To analyze the curvature function for extrema, the GWT was used:

$$HVT(k(S)) = \int_0^L \frac{k(S_1)}{\alpha(S - S_1)} dS_1,$$

where: $k(S)$ – curvature function; α – scale factor.

The point at which the GWT is either equal to 0 or changes its sign is taken as the CT position on the traced contour. The scale of GWT α is determined by the requirements for the accuracy and noise immunity of determining the CT coordinates.

3. Description of object localization by the position of the center of mass

The position of the center of mass of an object also uniquely determines its localization [14] and can be defined as the arithmetic mean of the coordinates of contour points or characteristic points.

Studies have shown that the calculation of the position of the centers of mass of contours can reduce errors in the description of the shape of the contour of an object by an average of two times.

The proposed method uses the position of object`s center of mass to generate a simplified depth map, which is a map of the positioning of objects with respect to their distances. Despite the inaccuracy of describing the localization by the position of objects center of mass extended in depth, such a positioning map is sufficient for a number of practical tasks solved by mobile navigation systems.

a b

Fig. 3. **Dependence of the difference in positions of the center of mass of objects on the distance: a – upon moving objects away; b – upon moving objects in**
Source: **compiled by the authors**

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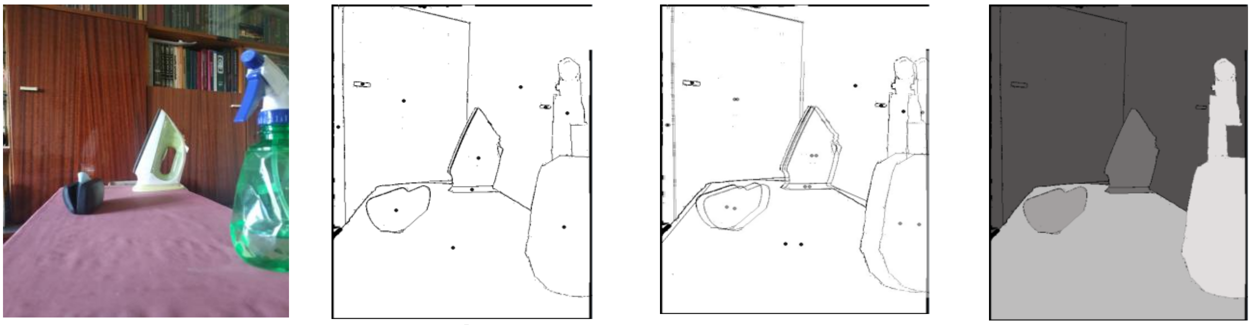

a b c d

Fig. 4. **Modeling the proposed method:**
a – scene image; b – contour description of the one of stereopair image;
c – stereopair images contour combination and mass centers evaluation; d – depth map coloring
Source: **compiled by the authors**

Depth map generation method

The proposed method includes the following steps.

1) Selection of the type of wavelet function for processing (determined by the features of the image in the application area), selection of parameters (coefficients and scales) of the wavelet function (depends on the required level of detail), selection of the object localization method (contour, by characteristic points, by the position of the center mass), which determines the error and processing time [15, 18].

2) Calculation of the localization of objects in the original image (Fig. 4a) using one of the above methods on each image of a stereopair (Fig. 4b).

3) Calculation of the difference values in the localization of individual objects it two images of a stereopair (Fig. 4c).

4) Coloring of the depth map or representing the image in terms of distance to the object (Fig. 4d) [19].

4. PROTOTYPING

A prototype of a mobile navigation system has been assembled and tested. The usage of two video cameras, a Raspberry Pi 3 microcomputer, and a depth contour map screen provides stereoscopic and panoramic “vision”, in other words, the ability to determine the presence of objects with their distances and get an overall picture in the field of “vision” of the system [19, 20]. The availability of an engine control unit allows mobile devices to bypass obstacles.

For the purpose of software implementation of the proposed solutions, software based on the OpenCV library was developed [21]. Interoperation of two video cameras is provided by software. This allows getting information about the distance to the object and its dimensions [22, 23].

The mobile navigation system prototype is powered by a 5V battery, which can be standard power bank, a portable power supply or an external battery. The current consumption depends on the complexity of the picture and varies in range of 500-800 mA, thus the power consumption is 2,5-4 Watts, which allows the use of the proposed solutions in mobile navigation systems.

5. CONCLUSION

This work is devoted to the development of a method for generation a depth map based on objects localization information in images of a stereopair. The proposed solutions implement the description of objects by the following informative elements: contours, characteristic points (points of the greatest curvature of the contour), the object’s center of mass. Moreover, to describe the contour of the image, it is proposed to use methods with adjustable detail level, which is implemented on the basis of the wavelet transform, which has frequency-selective properties. The novelty of this method is the simplification of the evaluation of the values of the stereo image difference, which is traditionally used to build a depth map based only on information about the localization of objects. The advantage of the method is that there is no need to position and calibrate cameras, which is important for mobile systems.

Prototyping of a mobile navigation system based on the Raspberry Pi 3 microcomputer was carried out. Software was developed based on the proposed solutions. Modeling confirmed the effectiveness of the proposed approach.

Generation of a depth map based on description of objects with the contour detection with adjustable detail level method, the degree of impact of noise and changes in illumination is reduced by an average of two times.

Calculation of the objects center mass position on a stereo image could significantly reduce the time for generating a simplified depth map (by an order of magnitude on average) and thereby significantly reduce energy costs with accuracy level, which is acceptable for a number of practical tasks.

The proposed method can significantly reduce the number of computational operations and, consequently, reduce the processing time of images of stereopair cameras, reduce power consumption (on average by a factor of two), and therefore it can be recommended for mobile navigation systems operating in conditions of limited computing and energy resources.

The method provides object detection and spatial positioning, makes it possible to obtain reliable information about the distance to objects for other subsystems that use technical vision in their operation, for example, navigation systems for visually impaired people, robotic devices, etc.

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Побудова карти глибин для мобільних навігаційних систем з урахуванням локалізації об’єктів на зображеннях

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АНОТАЦІЯ

Робота присвячена розробці методу побудови карти глибин, заснованого на обліку локалізації об'єктів на зображеннях, отриманих за допомогою стереопари. Запропоновані рішення реалізують опис об'єктів такими інформативними елементами: контурами, характерними точками (точками найбільшої кривизни контуру), центром мас об'єкта. Причому для опису контуру зображення запропоновано використовувати методи з регульованою детальністю, що реалізуються на основі вейвлет-перетворення, якому характерні частотно-виборчі властивості. Розкрито ідею побудови карти глибин на основі такого інформативного опису. Нововведенням даного методу є можливість одержання приблизної карти глибин за рахунок спрощення обчислення значень різниці стереозображень, яку традиційно використовують для побудови карти. Проведено макетування. Розроблено програмне забезпечення на основі запропонованих рішень. Макетування підтвердило ефективність запропонованого підходу. Запропонований метод дозволяє значно зменшити кількість обчислювальних

операцій і, отже, продуктивність та рекомендувати запропонований метод для мобільних навігаційних систем, що працюють в умовах обмежених обчислювальних та енергетичних ресурсів. Метод забезпечує виявлення об'єктів та просторове позиціонування, дає можливість отримувати достатню інформацію про відстань до об'єктів для інших підсистем, що використовують у своєму функціонуванні технічний зір, наприклад, навігаційні системи для людей з обмеженим зором, робототехнічні пристрої та ін.

Keywords: мобільні навігаційні системи; карта глибин; виділення контурів; локалізація об'єктів на зображенні; вейвлет-перетворення

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