UDC 681.5.01

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MULTI-BEAM OPTICAL SENSOR FOR MEASURING DRONE COORDINATES

The article presents a multi-beam optical sensor for measuring drone coordinates in three-dimensional space. The first part of this sensor is installed around a landing pad or a goods delivery pad. It forms a set of low-energy optical beams of a certain shape. Each beam transmits a digital code that characterizes its location relatively the pad. The second part of this sensor is a small set of miniature photodetector units that are fixed under the drone. The proposed technique based on the beam code analysis helps to calculate the drone coordinates relatively the pad. This sensor guarantees few centimetres accuracy, which is necessary for accurate drone taking off or landing without usage of an expensive digital camera or a human operator. The paper describes the classification of drone coordinate measurement techniques, sensor design, and experimental tests of the proposed optical sensor. The advantages and possible applications of these sensors are also discussed.

Keywords: *optical sensor, coordinate measurement, drone navigation, vision-based positioning, data fusion, multi-beam technique, coded beams.*

Introduction. Drones are already an important part of our lives. They are widely used for observation and remote sensing, rescue services, goods delivery, etc. Drone taking off, landing and, especially, goods delivery are carried out many times. It most cases human operators do these operations and, as a result, it increases the price and risk of drone usage. Modern techniques for automatic control of drones require digital cameras on stabilized gimbal, powerful computers and high-speed telecommunication units [1-9]. It also makes drones and drone usage expensive. For widespread implementation of drone goods delivery and other fields, drones must have a reliable and economical system for coordinate measurements during fully automatic taking off, landing and goods delivery. But any coordinate measurements using digital cameras or with the help of a human operator become very expensive and not reliable enough for numerous routine drone flights.

Goal and tasks. The goal of this study is to find and to study the compact and economical drone positioning system (DPS) that can work without usage of digital cameras and control of a human operator. This DPS should cover the gap between several meter accuracy of coordinate measurements in economical global position system (GPS) modules and the required accuracy equal to 0.25-0.5 m for accurate and automatic landing, taking off and goods delivery. To achieve the specified goal, the following tasks must be solved: study of the known techniques for drone coordinate measurements, identification of the best DPS design, creation of mathematical description of the proposed DPS and performance of experimental research that should confirm the correctness of the proposed solution.

Methods

1. Overview of techniques for drone coordinate measurement. All DPSs can be conventionally divided into two big categories: DPSs that use digital cameras and DPSs that do not use cameras (Figure 1). DPSs with digital cameras can be divided into systems in which the cameras are located on the ground and those in which the camera is located on the drone (Figure 1). The main idea of the first is to recognize the drone, track it and transfer information to the drone for its correction [1, 2]. The second, with the help of a camera, recognize markers on the ground, and based on their size and position, receive information about the location of the drone in space relative to these markers. Markers can be: objects, inscriptions (for example, a QR-code), light, and combinations thereof [3-9].

DPSs that do not use cameras use emitting devices and radiation receivers, which can be located both on the ground and on the drone in various combinations, [10-16] (Figure 1). Emitters can use different wavebands (infra-red (IR), visible, radio waves, etc.), receivers are selected according to the band that has been chosen. Descriptions of these DPSs are made in [17, 18].

DOI: 10.24025/2306-4412.1.2023.267070

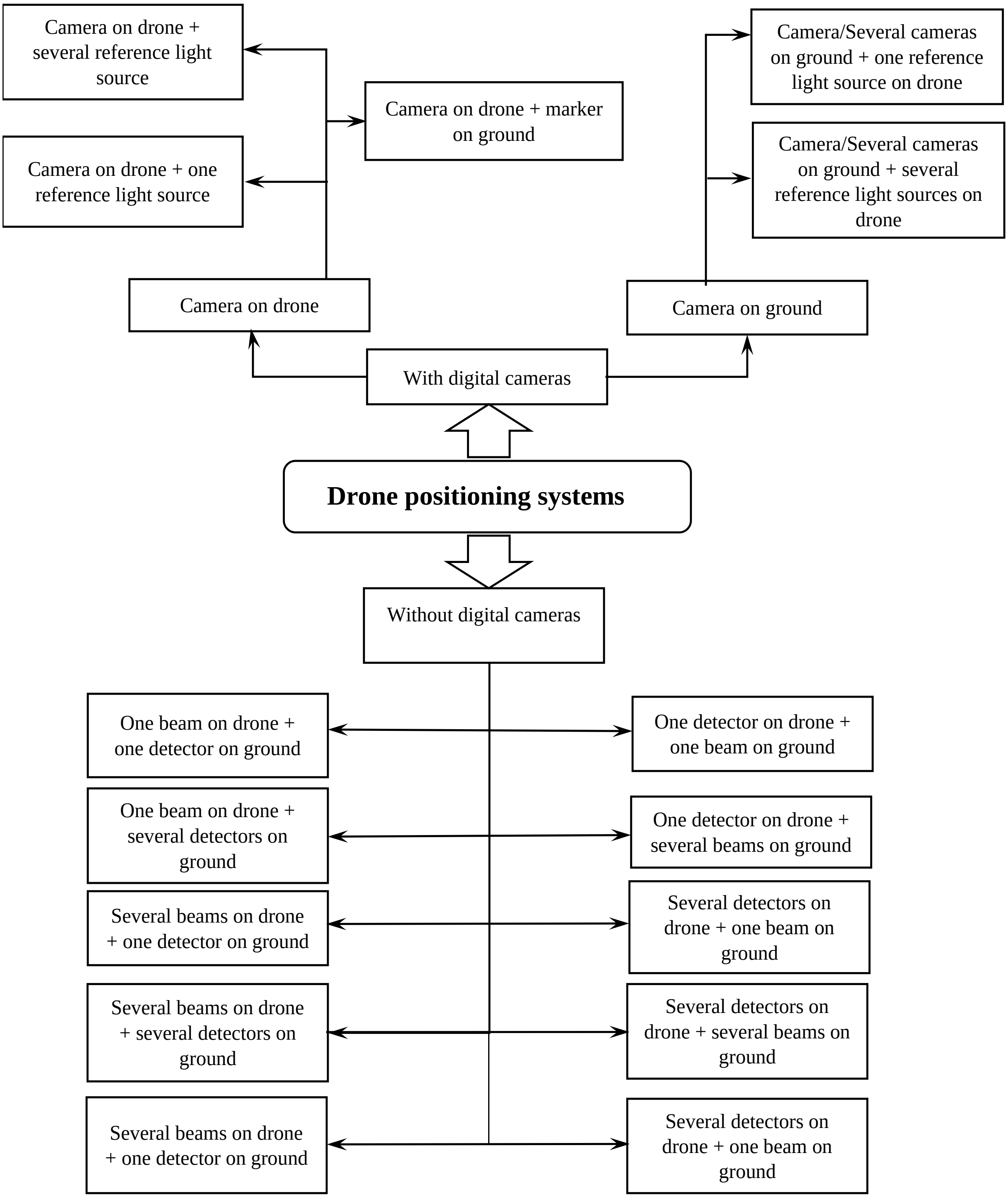

Figure 1. Classification of drone positioning systems

2. Description of the proposed DPS. The proposed DPS refers to systems that do not use cameras. The main idea of the proposed DPS is the application of the spatial structure of IR beams. These beams transmit coded data about the direction to the landing site in three-dimensional (3D) space. A drone is equipped with one or more small photodetector units that receive coded data from one or more optical beams.

The DPS consists of two parts: the first one is the illumination part installed on the ground around the landing site. The second part 8 is the receiving part. It is fixed on the drone (Figure 2) [19, 20].

DOI: 10.24025/2306-4412.1.2023.267070

The illumination part includes a power source 3, a control unit 2 and two or more beam formation units (BFU) 1, which illuminate low-energy IR beams 7. Each beam transmits digital codes that set the direction to the landing site in 3D space (Figure 2). The receiving part is just a few very small photo detectors 4 mounted on the bottom surface of the drone. They work only during landing, when they capture coded optical signals and send them to the flight controller (or drone computer) 6. The control unit 2 generates codes for each beam, and these codes are separated in time. Therefore, the photodetector units can record and analyze the codes of various beams. Analyzing the received codes – data about the direction to the landing site – this computer calculates the drone's path to it. Battery 5 supplies light-sensitive units 4, drone computer 6 and other drone units with electricity (Figure 2).

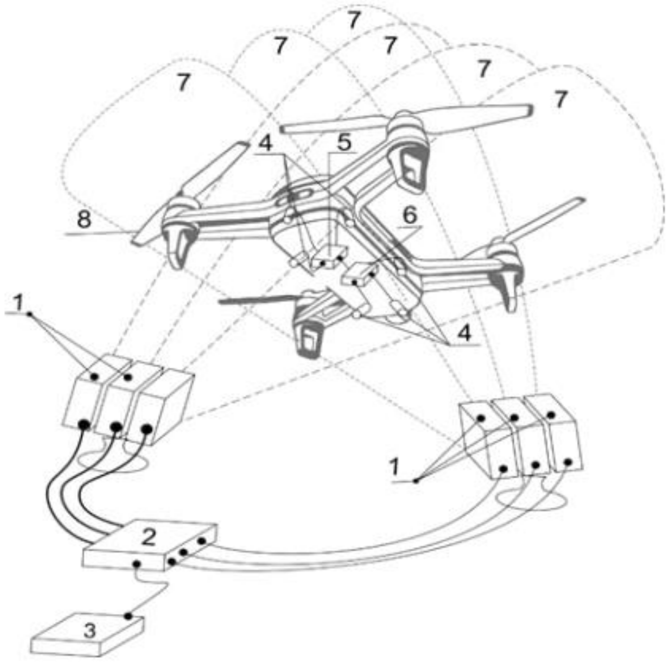

Figure 2. Proposed design of the multi-beam drone positioning system

3. Mathematical model of multi-beam DPS. The requirements for the proposed multi-beam DPS are as follows:

1. The DPS should be economical. This means that the number of illumination units and IR beams should be kept to a minimum.

2. The beams must cover a sufficient 3D volume around the landing pad without unlit areas, considering that all beams are the same.

3. The positioning system should be compact with the possibility of installation on any small plane.

4. The dimensions of the working area of the positioning system should be large enough for drones of different types and sizes.

5. The number of beams in the horizontal direction must not be even.

To meet the requirements, a beam geometry is chosen with only one illumination unit in vertical direction and two illumination units in horizontal direction.

To understand how much is needed by the radiation source on each block to ensure the required accuracy, it is necessary to carry out calculations using Figure 3 and Figure 4.

First, let's calculate horizontal beams (Figure 3). For this, it is necessary to set the positioning accuracy, which is equal to: R_P; the radius of the landing zone R_W, as well as the distance from the center of the landing zone to the radiation source L_B.

At the same time, it is necessary to fulfill the following requirement:

$$L_B > R_W > R_P.$$

The first step is to calculate the angular size of the landing pad $\Delta\alpha$. For this, using Figure 3 and the given parameters, we will get:

$$\Delta\alpha = 2 \cdot \arctan\left(\frac{R_P}{L_B}\right),$$

where R_P is landing pad radius; L_B is the distance between the center of the landing pad and the BFU; *arctan*() is inverse tangent function.

DOI: 10.24025/2306-4412.1.2023.267070

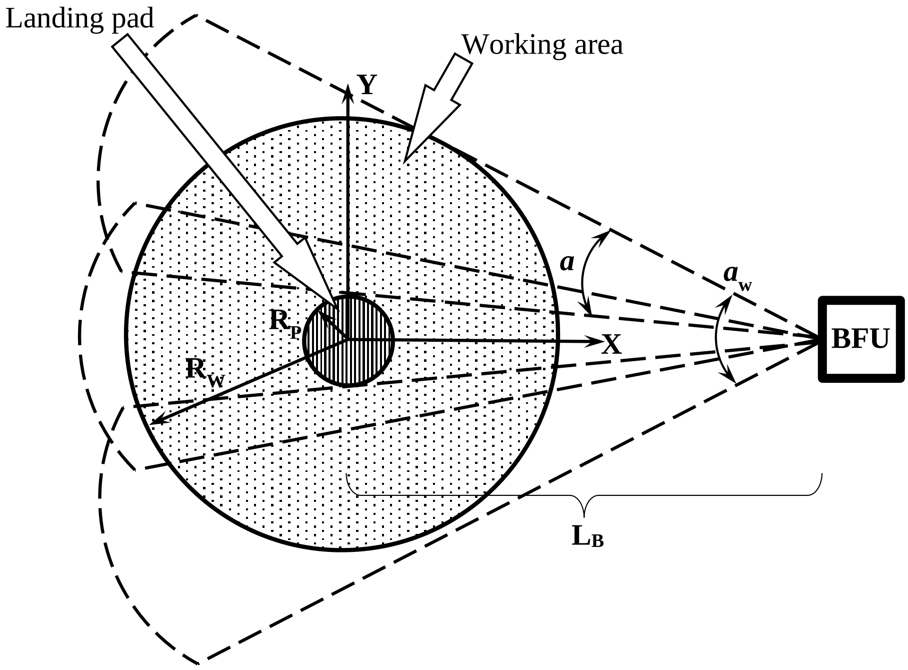

Figure 3. Horizontal beams in the multi-beam drone positioning system

In the next step, using Figure 3 and the initial parameters, we will calculate the radiation angle of the BFU block α_W:

$$a_W = 2 \cdot \arctan\left(\frac{R_W}{L_B}\right),$$

where R_W is the radius of the working area; L_B is the distance between the center of the landing pad and the BFU: $L_B > R_W$.

Having found the angles $\Delta\alpha$ and a_W, you can calculate the number of beams of the same thickness that fill the space given by the angle a_W, using the following formula:

$$N_d = \frac{a_W}{\Delta\alpha}.$$

Since N_d can only be an integer, it is necessary to round up to a larger number of beams.

Knowing that the beams overlap each other with a ratio of 1/3 to form the equal angular zones, as well as the number of identical N_d beams, you can calculate the number of radiation sources in one BFU:

$$N_S = \frac{N_d}{2} + 1.$$

N_d, N_S must be an integer. Therefore, it is necessary to round the obtained result to a larger value in order to cover all the working area of the system with beams.

Similarly, let's calculate vertical beams (Figure 4).

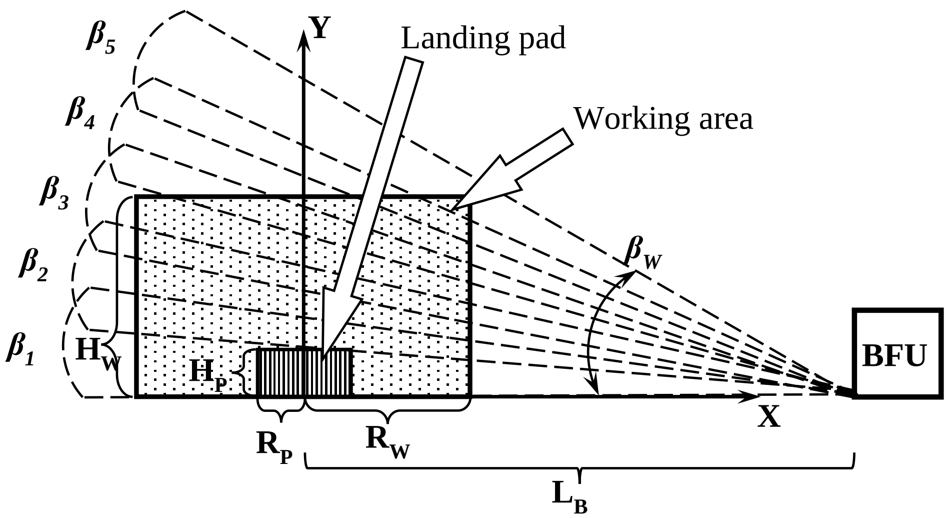

Figure 4. Vertical beams in the multi-beam drone positioning system

DOI: 10.24025/2306-4412.1.2023.267070

All beams are similar and have an overlapping area equal to 1/3 of the full size of the angle. This guarantees the absence of unlit areas between two beams (Figure 4).

As in the case of horizontal beams, to begin with, we will calculate the angular size of the precise positioning zone $\Delta\beta$:

$$\Delta\beta = \arctan\left(\frac{H_P}{L_B}\right),$$

where H_P is the height of landing pad; L_B is the distance between the center of the landing pad and the radiation block.

The next step is to calculate the angular size of the landing zone β_W:

$$\beta_W = \arctan\left(\frac{H_W}{L_B}\right),$$

where L_B is the distance between the center of the landing pad and the BFU; H_W is the height of the positioning working area.

Having found the angles $\Delta\beta$ and β_W, you can calculate the number of beams of the same thickness that fill the space given by the angle β_W, using the following formula:

$$N_k = \frac{\beta_W}{\Delta\beta}.$$

Since N_k can only be an integer, it is necessary to round up to a larger number of beams to accurately cover the working landing area.

Let's calculate the number of radiation sources in one BFU:

$$N_h = \frac{N_k}{2} + 1.$$

N_h, like N_k, cannot be a fraction, so it is necessary to round up to a larger value.

The total number of radiation sources on the three blocks will be equal to

$$N = 2 \cdot N_S + N_h.$$

For experiments, it is necessary to calculate the specific number of radiation sources in horizontal and vertical blocks of the BFU, which will be able to satisfy the given positioning accuracy. The results of calculations are presented in Table 1.

4. Experimental studies of multi-beam DPS prototype. To confirm the functionality of the proposed DPS, a working prototype of such a system was designed and assembled, and a set of experiments were conducted with it. To achieve the required forms of the indicatrix, various combinations of diaphragms were used on the illumination part, as well as the receiving part to reduce the influence of external interference.

The DPS prototype contains the illumination part, which is placed on the ground, and a receiving part, which is placed on the drone. The illumination part has a control unit in which there are an Atmega8 microcontroller [21], a power supply and three BFUs. Five radiation sources – IR light emitted diodes TSAL6100 [22] – are installed in each BFU.

Table 1. **Angular size and angular coordinates of the beams**

Parameters	Horizontal direction	Vertical direction
The size of the working area, m	$R_W = 0.5$	$H_W = 0.35$
Landing area size, m	$R_P = 0.1$	$H_P = 0.1$
The distance between the center of the landing site and the source of radiation, m	$L_B = 1.0$	
Corner overlap, corner degrees	$\Delta\alpha = 7$	$\Delta\beta = 4$
Angular size of the working area, angle degrees	$\alpha_W = 77$	$\beta_W = 59$
The number of identical beams	$N_S = 5$	$N_h = 5$
Total number of beams	N = 15	

The receiving part is located on the drone. It has a signal processing unit, a power source (a drone power source can be used) and photodetector units TSOP32156 with a frequency of 56kHz [23]. For visualization of drone coordinate this unit has an indicator – a set of light emitted diodes.

Results. The experimental research was carried out in various times and weather conditions, including summer, winter, sunny days, cloudy days, nights, etc. Figure 5 shows the experiment with one illumination unit and a drone with the indicator of the coded beams.

The experimental results showed that the proposed DPS works correctly. The receiving part gradually turned off the indicators as it deviated from the center of the receiving part. Table 2 shows the measured positioning deviations for different combinations of diaphragms used.

DOI: 10.24025/2306-4412.1.2023.267070

Discussion. The Table 2 shows that the best result was obtained with a combination of diaphragms on the emitting unit and a cone on the photodetector unit. The deviation at 1 m distance with such a combination is 180 mm. It means that accuracy of coordinate measurements can be evaluated as 1/3 of beam width – 60 mm when the distance is 1 m. It means that the accuracy 180-240 mm could be reached when distance is in the range 3-4 m. In this case DPS should have only two BFUs and minimum 5 emitters in each BFU. These experimental studies have confirmed the correctness of the proposed mathematical apparatus.

Figure 5. Drone on the landing platform during experiments with the proposed multi-beam drone positioning system

Conclusions. The scientific novelty is the new approach for measurements of drone coordinates during taking off, landing and goods delivery. This approach is application of multiple IR beams with definite angular orientations and angular dimensions that cover 3D space above a landing pad. Each beam transmits a digital code, and a drone can calculate its coordinates using received beam codes. As a result, this DPS can guarantee the coordinate measurement accuracy less than 180-240 mm in a zone with radius up to 1-2 m.

Table 2. **Experimental measured beam width**

The distance from the centre of the landing pad to the BFU	Emitter without diaphragms + photodetector unit with a cylinder diaphragm		Emitter without diaphragms + photodetector unit with a cone diaphragm		Emitter with diaphragms + photodetector unit with a cylinder diaphragm		Emitter with diaphragms + photodetector unit with a cone diaphragm	
	Central beam (mm)	Edge beam (mm)	Central beam (mm)	Edge beam (mm)	Central beam (mm)	Edge beam (mm)	Central beam (mm)	Edge beam (mm)
200 mm.	150	190	150	220	80	150	70	130
500 mm.	290	340	220	300	190	260	100	165
1000 mm.	460	540	300	365	400	490	180	300

The proposed DPS closes the gap between the accuracy of economical GPS modules and the accuracy necessary for accurate taking off, landing and goods delivery. It makes possible accurate and fully automatic drone taking off, landing and goods delivery.

The practical value is possibility to manufacture the commercial multi-beam DPSs using the solutions from experimentally tested DSP prototype. These solutions include the BFU design, hardware and software for signal generations for coded beams, the design of the indicator for measurements of beam orientations and beam

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geometry, etc. It should be noted, that the proposed DPS can be used in technical education for illustrations and practical works in disciplines such as photonics, microcontrollers and geometry.

The future activity should be concentrated on implementation of the proposed DPS in routine goods delivery operations made by drones, including the development of the software for reliable drone control in 3D space covered by multiple coded beams, registration and analysis of factors that decrease accuracy of coordinate measurements, and evaluation of economical profit from implementation of the proposed DPS.

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DOI: 10.24025/2306-4412.1.2023.267070

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БАГАТОПРОМЕНЕВА ОПТИКО-ЕЛЕКТРОННА СИСТЕМА ДЛЯ ВИМІРЮВАННЯ КООРДИНАТ ДРОНА

В статті представлено багатопроменеву оптико-електронну систему для вимірювання координат дрона в тривимірному просторі. Всі існуючі системи умовно можна поділити на два класи: системи, які використовують камери, і системи, які не використовують камери. В нашій роботі показано новий метод системи, яка не використовує камеру. Одна частина цієї системи встановлюється навколо посадкової площадки або площадки, над якою необхідно здійснити позиціонування. Він утворює набір низькоенергетичних оптичних променів певної форми. Кожний промінь передає цифровий код, який характеризує його розташування відносно площадки. Друга частина цієї системи – це невеликий набір мініатюрних фотодетекторів, які закріплюються під дроном. Запропонована методика на основі порівняння коду променя дозволяє розрахувати координати дрона відносно площадки. Ця система гарантує точність у кілька десятків сантиметрів, що необхідно для точного зльоту чи посадки дрона без використання дорогої цифрової камери чи людини-оператора. В статті запропоновано розрахунок кількості однакових променів випромінювальної частини, які необхідні для досягнення встановленої точності. Розрахунок проводився в двох напрямках: горизонтальному та вертикальному. Це дає змогу корегувати положення дрона у тривимірному просторі як для зльоту/посадки, так і для підтримки одного положення на висоті. Представлений працюючий прототип системи, яка складається з випромінювального блока на землі та приймального блока на дроні. Випромінювальний блок формує у просторі кодовані промені, які надходять до приймального блока. Приймальний блок оброблює отриману інформацію і надсилає сигнали до блока управління дроном для корегування його положення відносно посадкової зони. Показано результати досліджень при застосуванні різних діафрагм для світлодіодів та фотоприймальних пристроїв. Вибрано найкращий варіант конструкції блоків та отримано оцінку похибок вимірювання координат дронів.

Ключові слова: *оптичний датчик, вимірювання координат, навігація безпілотника, позиціонування на основі бачення, злиття даних, багатопроменева техніка, кодовані промені.*

Стаття надійшла 14.11.2022
Прийнято 15.12.2022

DOI: 10.24025/2306-4412.1.2023.267070