Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2023, № 1 (109) https://doi.org/10.33108/visnyk_tntu2023.01
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

UDC 681.5.01

COORDINATE MEASUREMENT IN MULTI-BEAM DRONE POSITIONING SYSTEM

Dmytro Averin; Volodymyr Borovytsky

National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine

Summary. *The multi beam drone positioning system for automatic measurements of drone coordinates is presented. One part of this system is installed round a landing pad or a goods delivery pad. It forms a set of low-energy optical beams of definite shapes in three-dimensional space. Each beam transmits a digital code that characterizes its location relatively this pad. Second part of this system is a small set of miniature photodetector units that are fixed under a drone. The paper describes the technique based of the beam code analysis for calculation of drone coordinates relatively a landing pad. This system guarantees the accuracy that is necessary for accurate drone taking off, landing or goods delivery without usage of an expensive digital camera or a human operator. The advantages and possible applications of these sensors are also discussed.*

Key words: *drone positioning system, multi-beam technique, coordinate measurement, drone navigation, coded beams.*

https://doi.org/10.33108/visnyk_tntu2023.01.080 *Received 27.01.2023*

Introduction. The market for transportation by drones in 2023 is estimated at $15.42 billion. Experts predict that this market will increase by approximately 21% every year. According to Emergen Research, this figure will reach $32 billion by 2031 [1]. The use of drones in logistics can bring many advantages to the logistics and transportation sectors: cheaper, faster deliveries, making companies less dependent on the human factor, etc.

To deliver goods to consumers, drones must accurately determine their coordinates relative to the destination point with an error of a range ± 25 cm. It helps to deliver goods to cafe tables, balconies in houses, car roofs, containers in the yard, etc. In most cases, economic coordinate measurement systems, which mostly use global positioning system (GPS) that cannot provide coordinates with errors smaller several meters. That is why the sophisticated and expensive digital cameras on stabilized gimbals and high-speed data transmission electronics with control by a human operator or complex image processing programs are used to ensure accurate delivery of cargo, take-off and landing of drones. It increases the price of goods delivery cargo operation, drones and drone exploitation. Of course, it sufficiently decreases drone payload and goods delivery distance [2, 3].

The goal of the paper is to propose the drone positioning system (DPS) and the procedure for drone coordinate measurements that can work and that guarantees the drone positioning relatively a landing pad or a goods delivery place with accuracy smaller than 0.25 m without usage of digital camera, human control or sophisticated image processing software.

Methods. The proposed DPS uses the spatial structure of low energy infra-red beams. These beams transmit codes that helps to calculate the drone coordinates in the three-dimensional (3D) space round a landing pad. This DPS consists of two parts (Fig. 1) [4–8]. The first one is the illumination part installed on ground around the landing site. The second part 8 is the receiving part fixed on a drone.

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 infra-red (IR) beams 7. Each beam transmits digital code (Fig. 1). The receiving part is just a few very small photodetector units 4 mounted on the bottom surface of the drone. They work only during landing, when they capture coded optical signals from BFU and send them to the flight controller or drone computer 6. The control unit 2 generates special codes for each beam. Therefore, the photodetector units can read out these codes and send them to a drone computer 6. The drone computer performs calculation of the drone coordinates. Battery 5 supplies photodetector units 4, drone computer 6 and other drone units with electrical power (Fig. 1).

Let's consider the procedure of coordinate calculation in the proposed DPS. We select economical DPS design with two BFUs, each BFU illuminate the orthogonal spatial structure of 5 x 3 overlapped coded beams (Fig. 2). It is sufficient to create 9 x 5 = 45 zones for coordinate measurements using one BFU. Application of two such BFUs helps to from 45 x 45 = 2025 zones in 3D space above a landing pad. The detailed description of spatial beam structure for the proposed DPS was made in [3–5].

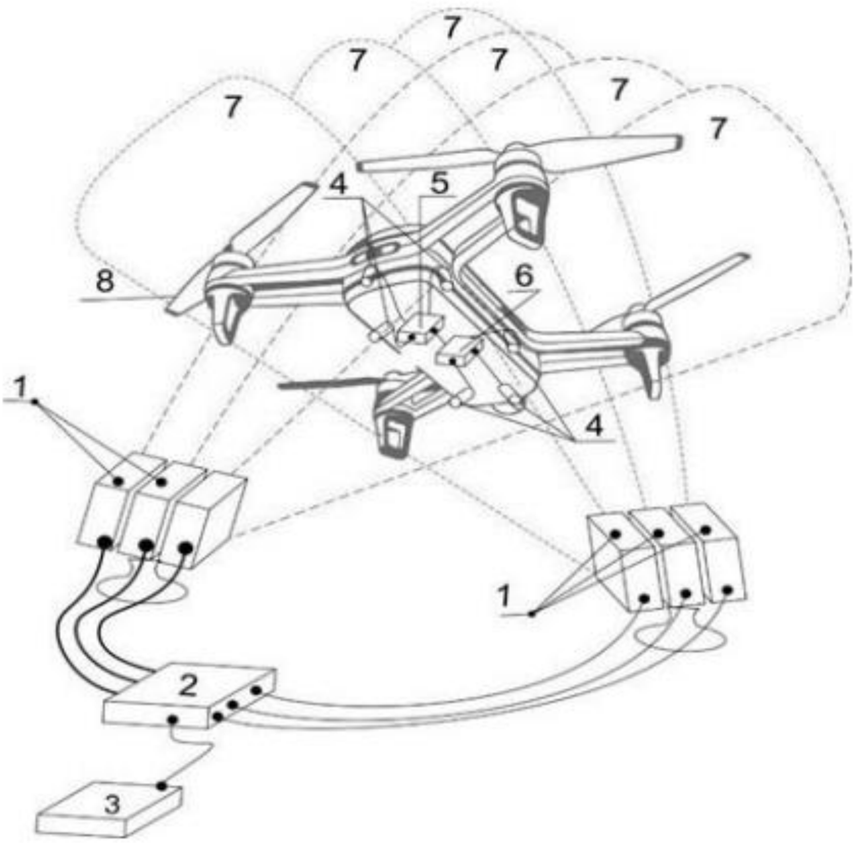

Figure 1. The proposed multi-beam drone positioning system

The input data necessary for coordinate calculation include the absolute coordinates of a landing pad center, the coordinates of two or more BFUs relatively the landing pad center, the angular coordinates of the central beam in horizontal and vertical directions, for example – (αBFU1, βBFU1) and the angular steps of coded beams in horizontal and vertical directions, for example – (ΔαBFU1, ΔβBFU1) (Fig. 2). It requires that each BFU has a digital compass for collecting horizontal angles of beams and a liquid level for setting correct vertical angles of beams.

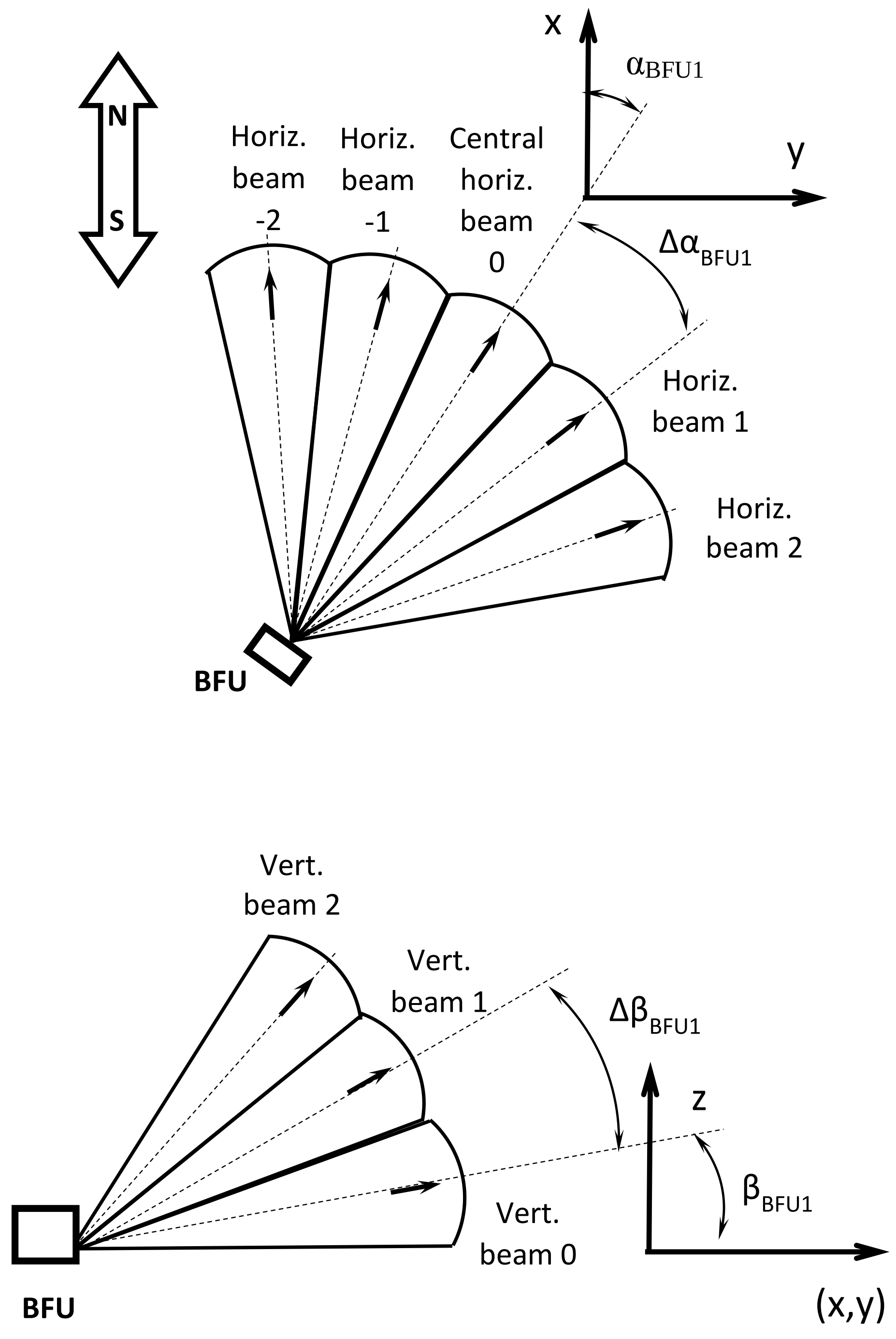

Figure 2. 3D coded beam structure of BFU № 1

All the beams of all BFUs transmit the digital packages of the same format. We select 64 bits digital package that contains the constant part for all beams – a DPS identification number, start and stop bits and the variable part – two or three 15 bits data used as beam codes. (Fig. 3). For example, spatial structure of 15 beams of BFU № 1 is presented by 15 bits: each beam sets the value 1 only in the corresponded bit ant it does not transmit data when other bits must be transmitted. Well-known IR remote control systems uses the definite frequency to transmit digital packages sequentially [9]. They applies compact and economical photodetector units for reading out these digital packages [10]. The digital output signal pin of this unit can be directly attached to the drone computer. The drone computer can capture the digital package and extract the data about the beams in which a drone flies.

When the drone computer received the digital package, it can easy extract beam bits using bitwise shift and bitwise and operations. The following code written in C programming language illustrates this extraction:

```
#define Mask_15_bits   0x7F

bfu_1_beam_code = (  received_64bits_code  >>  ( 32 + 1 ) ) &  Mask_15_bits ;
bfu_2_beam_code = (  received_64bits_code  >>  ( 16 + 1 ) ) & Mask_15_bits ;
```

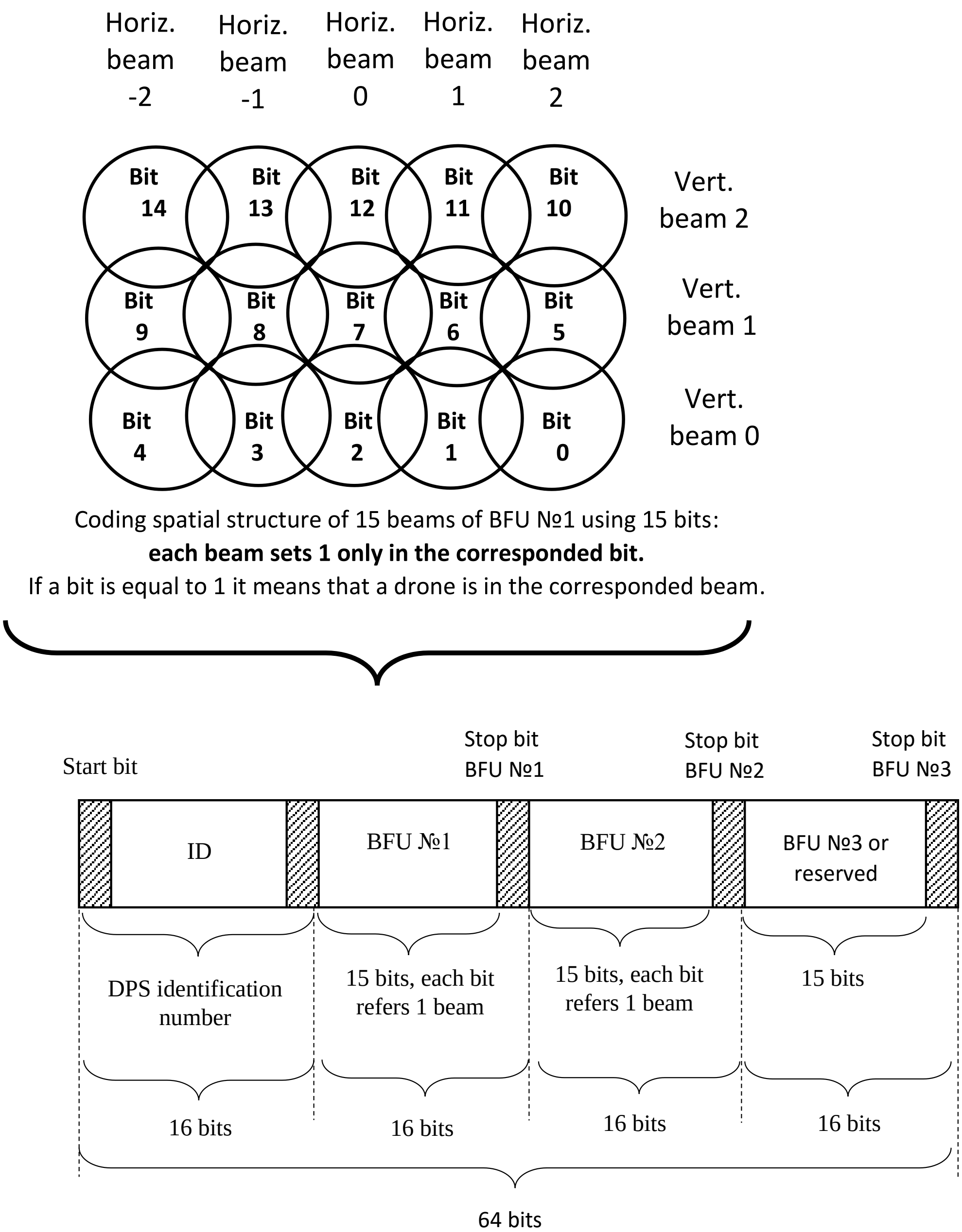

Figure 3. Digital package of BFUs

Knowing the spatial structure of IR beams it is possible to get the horizontal and vertical beam numbers for both BFU: if a bit is equal to 1 it means that a drone is in the corresponded beam (Fig. 3). The following code show how to get the beam numbers:

```
#define Mask_5_bits   0x1F  //   Mask_5_bits   = 0b00011111

cx_0 =  bfu_1_beam_code               & Mask_5_bits    ;
cx_1 =  ( bfu_1_beam_code >> 5 )    & Mask_5_bits    ;
cx_2 =  ( bfu_1_beam_code >> 10 )  & Mask_5_bits    ;
a1_angle_index = cx_0 | cx_1 | cx_2 ;

cy_0 = ( cx_0 == 0 ) ? : 0 ; 1 ;
cy_1 =  ( cx_1 == 0 ) ? : 0 ; 1 ;
cy_2 =  ( cx_2 == 0 ) ? : 0 ; 1 ;
b1_angle_index = cy_0 | cy_1 | cy_2 ;

cx_0 =  bfu_2_beam_code              & Mask_5_bits    ;
cx_1 =  ( bfu_2_beam_code >> 5 )    & Mask_5_bits    ;
cx_2 =   ( bfu_2_beam_code >> 10 ) & Mask_5_bits    ;
a2_angle_index = cx_0 | cx_1 | cx_2 ;

cy_0 = ( cx_0 == 0 ) ? : 0 ; 1 ;
cy_1 =  ( cx_1 == 0 ) ? : 0 ; 1 ;
cy_2 =  ( cx_2 == 0 ) ? : 0 ; 1 ;
b2_angle_index = cy_0 | cy_1 | cy_2 ;
```

Table 1

Calculation of horizontal beam angles

a1_angle_index value	Horiz. beam number	Angle α1	Comment
00000	None	None	Error: no beams identified
00001	2	αBFU1 + 2·ΔαBFU1	–
00011	Overlap 2 and 1	αBFU1 + 1.5·ΔαBFU1	–
00010	1	αBFU1 + ΔαBFU1	–
00110	Overlap 1 and 0	αBFU1 + 0.5·ΔαBFU1	–
00100	0	αBFU1	Central beam
01100	Overlap -1 and 0	αBFU1 – 0.5·ΔαBFU1	–
01000	-1	αBFU1 – ΔαBFU1	–
11000	Overlap -2 and -1	αBFU1 – 1.5·ΔαBFU1	
10000	-2	αBFU1 – 2·ΔαBFU1	–
Otherwise	None	None	Error: beam combination is not correct

Using the input data about the angular orientation and angular steps of horizontal and vertical beams of BFU № 1 (αBFU1, βBFU1, ΔαBFU1, ΔβBFU1) and the BFU № 2 (αBFU2, βBFU2, ΔαBFU2, ΔβBFU2) it is possible to calculate the angles of each beam of both BFUs

(Fig. 2, 3). Taking into account the possible beam overlapping the formulas for angle calculations may be written in table form (Table 1, 2). These tables can be represented as digital arrays for both BFUs. It simplifies the code for angle calculations:

a1_angle = a1_table[a1_angle_index] ;
b1_angle = b1_table[b1_angle_index] ;
a2_angle = a2_table[a2_angle_index] ;
b2_angle = b2_table[b2_angle_index] ;

Table 2

Calculation of vertical beam angles

b1_angle_index value	Vert. beam number	Angle β1	Comment
000	None	None	Error: no beams identified
100	2	βBFU1 + 2·ΔβBFU1	–
011	Overlap 2 and 1	βBFU1 + 1.5·ΔβBFU1	–
010	1	βBFU1 + ΔβBFU1	–
011	Overlap 1 and 0	βBFU1 + 0.5·ΔβBFU1	–
001	0	βBFU1	–
Otherwise	None	None	Error: beam combination is not correct

When the angles (α1, α2) are found and the coordinates (x1, y1) of BFU № 1 and (x2, y2) of BFU № 2 are known we can calculate the drone coordinates (xD, yD) relatively the center of a landing pad (Fig. 4). The necessary conditions for coordinate calculations are the following:

1) The photosensitive unit should readout at least one beam code from BFU № 1 and one beam code – from BFU № 2.

2) The angles (α1, α2) should be different α1 ≠ α2. It means that the beams should cross each other.

3) The beam code combination should be correct. It means that only one or two bits of neighbor horizontal and vertical beams should be present in the digital package (Fig. 3, Table 1, 2).

The drone coordinates (xD, yD) can be found as the coordinate of intersection of two lines in (x,y) plane (Fig. 4) [11]:

$$y_D = tan(\alpha_1) * (x_D - x_1) + y_1$$

$$y_D = tan(\alpha_2) * (x_D - x_2) + y_2$$

$$tan(\alpha_1) * x_D - tan(\alpha_1) * x_1 + y_1 = tan(\alpha_2) * x_D - tan(\alpha_2) * x_2 + y_2$$

$$\big(tan(\alpha_1) - tg(\alpha_2)\big) * x_D = tan(\alpha_1) * x_1 - y_1 - tan(\alpha_2) * x_2 + y_2$$

$$\begin{cases} x_D = \dfrac{tan(\alpha_1) * x_1 - tan(\alpha_2) * x_2 - (y_1 - y_2)}{tan(\alpha_1) - tan(\alpha_2)} \\ y_D = tan(\alpha_1) * (x_D - x_1) + y_1 \end{cases} \quad (1)$$

where (xD, yD) – the drone coordinates; (x1, y1), (x2, y2) – the coordinates of BFU № 1 and BFU № 2, respectively; (α1, α2) – the horizontal angles of registered beams from BFU № 1 and BFU № 2, respectively; tan() – the trigonometric tangent function.

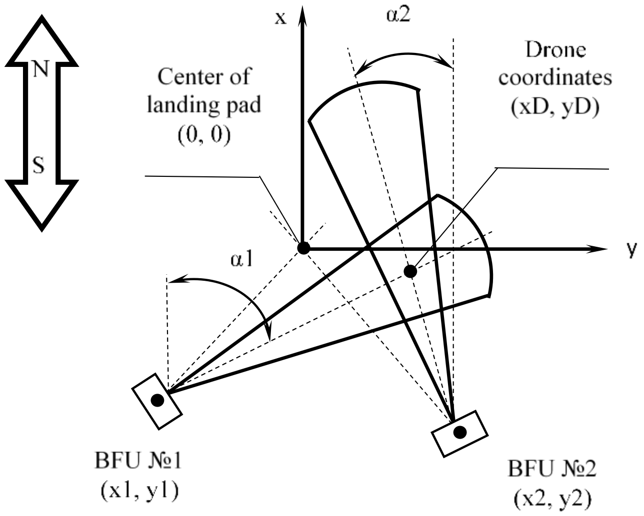

Figure 4. Calculation of drone coordinates relatively a landing pad

In case of $tan(\alpha_1) = \pm\infty$ the expression (1) has the following form:

$$\begin{gathered} x_D = x_1 \\ y_D = tan(\alpha_2) * (x_D - x_2) + y_2 \end{gathered} \quad (2)$$

In case of $tan(\alpha_2) = \pm\infty$ the expression (1) has the form similar to (2):

$$\begin{gathered} x_D = x_2 \\ y_D = tan(\alpha_1) * (x_D - x_1) + y_1 \end{gathered} \quad (3)$$

The direction to the center of a landing pads is defined by the current drone coordinates:

$$\vec{v} = \left(-\frac{x_D}{\sqrt{x_D^2 + y_D^2}}, -\frac{y_D}{\sqrt{x_D^2 + y_D^2}} \right) \quad (4)$$

where $\vec{v}$ – the vector that specifies the direction to the center of a landing pad, $\lfloor \vec{v} \rfloor = 1$.
The calculation of coordinate zD – the current drone attitude becomes possible when the coordinates (xD, yD) are already found (Fig 2, 4):

$$\begin{gathered} z_{D1} = tan(\beta_1) * L_1 = tan(\beta_1) * \sqrt{(x_D - x_1)^2 + (y_D - y_1)^2} \\ z_{D2} = tan(\beta_2) * L_2 = tan(\beta_2) * \sqrt{(x_D - x_2)^2 + (y_D - y_2)^2} \\ L_1 = \sqrt{(x_D - x_1)^2 + (y_D - y_1)^2} \\ L_2 = \sqrt{(x_D - x_2)^2 + (y_D - y_2)^2} \end{gathered} \quad (5)$$

where zD – the drone coordinates along z axis, it is current drone attitude; L1, L2 – the distance from a drone to BFU № 1 and BFU № 2 in the plane (x,y), respectively; (β1, β2) – the vertical angles of registered beams from BFU № 1 and BFU № 2, respectively.

As a result, the drone coordinate (xD, yD, zD) are calculated using the beam codes from IR coded beams in the proposed DPS and the formulas (1)-(5) (Fig. 1). If a multi-beam DPS contains three BFUs it is necessary to perform the coordinate calculations (1)-(5) for all combinations of two BFUs from three ones. It guarantees high reliability of drone coordinate measurements due to averaging of measurement results. The drone can use its relative coordinates (xD, yD, zD) and the direction $\vec{v}$ for fully automatic taking off, landing or goods delivery.

Results. To confirm that the proposed technique for drone coordinate measurements is applicable the working prototype of multi-beam DPS was designed, assembled and tested [6–8] (Fig. 5). DPS can work with two or three BFUs and each BFU illuminates five overlapping coded IR beams. method of coordinate measurement, an experimental setup was built. For indication of IR coded beams and drone coordinates the special unit with light emitted diodes was fixed under a drone as its payload (Fig. 5). The numerous experiments made in various weather conditions – including summer, winter, sun days, cloudy days, nights etc. – confirm ability of the proposed DPS to perform accurate and reliable coordinate measurements. Accuracy of coordinate measurements was evaluated as 1/3 of beam width – approximately 60 mm when the distance is 1 m. As a result, the accuracy 200–250 mm was reached when distance from BFUs and a center of a landing pad is in range 3–4 m.

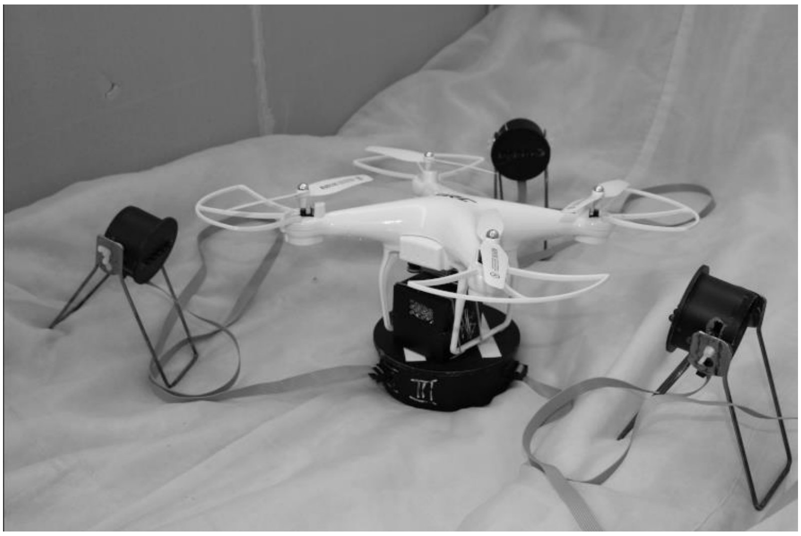

Figure 5. Drone and the proposed multi-beam drone positioning system

Discussion. The experimental research has been proven that the proposed multi-beam DPS and the corresponded mathematical apparatus for drone coordinate measurements can close the gap between accuracy of economical GPS modules in range of several meters and the necessary accuracy for automatic taking off, landing or goods delivery in range of 0.25–0.5 meters. The advantages of this DPS are economical design of BFUs, application of compact and economical photosensitive units on drones, fully automatic and fast coordinate measurements, ability to operate when a landing pad with BFUs moves in 3D space and etc.

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 coded beams with definite angular orientations and angular dimensions that cover

3D space above a landing pad. It has been confirmed that 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. The proposed DPS 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 IR coded beams, the design of the indicator for measurements of beams orientations and beam geometry, the mathematical apparatus (1)–(5) and code fragments written in C programming language.

The future activity should be concentrated on design of commercially available DPSs, their implementations in routine goods delivery operations made by drones, including development of the software for automatic taking off, landing and goods delivery based on the proposed technique for drone coordinate measurements.

References

1. Gunjan M., Sonia M., “Drone Package Delivery Market”, report of Allied market research. Sep. 2022. P. 339. Report Code: A07127.
2. Jeon H. Harriet and Lucarelli, Claudio and Mazarati, Jean Baptiste and Ngabo, Donatien and Song, Hummy. “Leapfrogging for Last-mile Delivery in Health Care”. October 12. 2022. URL: http://dx.doi.org/10.2139/ssrn.4214918. https://doi.org/10.2139/ssrn.4214918
3. Amazon Staff “Amazon Prime Air prepares for drone deliveries”. June 13. 2022. URL: https://www.aboutamazon.com/news/transportation/amazon-prime-air-prepares-for-drone-deliveries
4. D. Averin, V. Borovytsky and V. Mykytenko, “Drone positioning systems that uses digital cameras,” Bulletin of Kyiv Polytechnic Institute Series Instrument Making. July 2022. URL: http://dx.doi.org/10.20535/1970.63(1).2022.260632. https://doi.org/10.20535/1970.63(1).2022.260632
5. D. Averin, V. Borovytsky and S. Tuzhanskyi, “Local positioning system for drones without usage of digital cameras”. Optoelectronic Information-Power Technologies. Vol. 42. No. 2. P. 5–11. October 2022. URL: http://dx.doi.org/10.31649/1681-7893-2021-42-2-5-11. https://doi.org/10.31649/1681-7893-2021-42-2-5-11
6. V. Borovytsky and D. Averin “Optical-Electronic positioning system”. Ukraine Patent 141943, 2020.
7. V. Borovytsky and D. Averin “Optical sensor for drone coordinate measurements,” Proc. SPIE. Vol. 11352. 2020. https://doi.org/10.1117/12.2555392
8. Averin D., & Borovytskyi V. (2023). Multi-beam optical sensor for measuring drone coordinates. Bulletin of Cherkasy State Technological University. (1). P. 5–12. URL: https://doi.org/10.24025/2306-4412.1.2023.267070.
9. Vishay Semiconductors, “TSAL6100 High Power Infrared Emitting Diode, 940 nm,” 2019. URL: https://www.vishay.com/docs/81009/tsal6100.pdf.
10. Vishay Semiconductors, “TSOP32156 IR Receiver Modules for Remote Control Systems,” 2019. URL: http://www.vishay.com/docs/82490/tsop321.pdf.
11. Anderson, “Fundamentals of aerodynamics”, 6th ed. Columbus, OH: McGraw-Hill Education, 2016.

Список використаних джерел

1. Gunjan M., Sonia M., «Drone Package Delivery Market», звіт Allied market research. Вересень 2022. C. 339. Report Code: A07127.
2. Jeon H. Harriet and Lucarelli, Claudio and Mazarati, Jean Baptiste and Ngabo, Donatien and Song, Hummy, «Leapfrogging for Last-mile Delivery in Health Care», 12 жовтня 2022. URL: http://dx.doi.org/10.2139/ssrn.4214918. https://doi.org/10.2139/ssrn.4214918
3. Amazon Staff «Amazon Prime Air prepares for drone deliveries», 13 червня 2022. URL: https://www.aboutamazon.com/news/transportation/amazon-prime-air-prepares-for-drone-deliveries.
4. Аверін Д., Боровицький В., Микитенко В. «Системи позиціонування для дронів, які використовують цифрові камери» Вісник Київського політехнічного інституту. Серія Приладобудування. Липень 2022. URL: http://dx.doi.org/10.20535/1970.63(1).2022.260632. https://doi.org/10.20535/1970.63(1).2022.260632
5. Аверін Д., Боровицький В., Тужанський С., «Локальні системи позиціонування дронів без використання цифрових камер». Оптико-електронні інформаційно-енергетичні технології. Жовтень 2022. № 2. С. 5–11. URL: http://dx.doi.org/10.31649/1681-7893-2021-42-2-5-11. https://doi.org/10.31649/1681-7893-2021-42-2-5-11
6. Боровицький В., Аверін Д., «Оптико-електронна система позиціонування»: пат. на корисну модель України № 141943, 2020.

7. Borovytsky V. and Averin D. «Optical sensor for drone coordinate measurements». Proc. SPIE. Vol. 11352. 2020. https://doi.org/10.1117/12.2555392
8. Аверін Д., Боровицький В. Багатопроменева оптико-електронна система для вимірювання координат дрона. Вісник Черкаського державного технологічного університету. 2023. 1). С. 5–12. URL: https://doi.org/10.24025/2306-4412.1.2023.267070.
9. Vishay Semiconductors «TSAL6100 High Power Infrared Emitting Diode, 940 nm,» 2019. URL: https://www.vishay.com/docs/81009/tsal6100.pdf.
10. Vishay Semiconductors «TSOP32156 IR Receiver Modules for Remote Control Systems,» 2019. URL: http://www.vishay.com/docs/82490/tsop321.pdf.
11. Anderson «Fundamentals of aerodynamics», 6-те видання, Колумбія, McGraw-Hill Education, 2016.

УДК 681.5.01

ВИМІРЮВАННЯ КООРДИНАТ У БАГАТОПРОМЕНЕВІЙ СИСТЕМІ ПОЗИЦІОНУВАННЯ ДРОНІВ

Дмитро Аверін; Володимир Боровицький

Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ, Україна

Резюме. *Представлено багатопроменеву оптико-електронна систему позиціонування дрона для автоматичного вимірювання координат. Система складається з двох частин. Перша частина цієї системи встановлюється навколо посадкової площадки або площадки доставки товарів. Вона формує набір низькоенергетичних оптичних пучків певної форми в тривимірному просторі. Кожен промінь передає цифровий код, який характеризує його розташування відносно даної площадки. Друга частина цієї системи – невеликий набір мініатюрних блоків фотоприймачів, які закріплюються під дроном. Описано методику, засновану на аналізі коду променя для розрахунку координат дрона відносно посадкової площадки. Також описано алгоритм дій при вимірюванні координат дрона. Предсталені частини програмного забезпечення, які реалізують описаний алгоритм. Запропонована система гарантує точність, необхідну для точного зльоту, посадки або доставки вантажів без використання дорогої цифрової камери або людини-оператора. Також обговорено переваги та можливості застосування цих датчиків. Наукова новизна полягає в новому підході до вимірювання координат дронів під час зльоту, посадки й доставки вантажів. Практичною цінністю є можливість виготовлення комерційних багатопроменевих оптико-електронних систем позиціонування з використанням рішень із експериментально випробуваного прототипу системи позиціонування. Ці рішення включають конструкцію блока випромінювання, апаратне та програмне забезпечення генерації сигналів для ІЧ-кодованих променів, конструкцію індикатора для вимірювання орієнтації та геометрії променів, математичний апарат і фрагменти коду, написані мовою програмування С.*

У майбутньому діяльність повинна бути зосереджена на розробленні комерційно доступних багатопроменевих оптико-електронних систем позиціонування, їх реалізації в звичайних операціях доставки вантажів, що здійснюються безпілотниками, включаючи розроблення програмного забезпечення для автоматичного зльоту, посадки й доставки вантажів на основі запропонованої методики вимірювання координат дрона.

Ключові слова: *система позиціонування дрона, багатопроменева техніка, вимірювання координат, навігація дрона, кодовані промені.*

https://doi.org/10.33108/visnyk_tntu2023.01.080 *Отримано 27.01.2023*