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Kadylnykova Tatyana, Doctor of Technical Sciences, Professor, Professor of the Mechatronic
Кадильникова Т.М., доктор технічних наук, професор, професор кафедри механотроніки
ORCID: 0000-0003-0817-9466
e-mail: kadilnikovatm@ukr.net

Savchuk Illia, PhD, postgraduate student
Савчук І.В., PhD, здобувач третього (доктора філософії) рівня вищої освіти
ORCID: 0009-0007-0422-0712
e-mail: ilya.savik@gmail.com

Nekrasov Valerii, PhD, postgraduate student
Некрасов В.Є., PhD, здобувач третього (доктора філософії) рівня вищої освіти
ORCID: 0000-0002-9119-0529
e-mail: nekrasov.valery97@gmail.com

Oles Honchar Dnipro National University, Dnipro
Дніпровський національний університет імені Олеся Гончара, м. Дніпро

AUTONOMOUS POSITIONING ALGORITHM UNMANNED AIRCRAFT

АЛГОРИТМ АВТОНОМНОГО ПОЗІЦІОНУВАННЯ БЕЗПІЛОТНОГО ЛІТАЛЬНОГО АПАРАТУ

A new positioning algorithm was developed and implemented, in which the method of finding correspondence by creating patterns was used to search for an image element on a terrain map, which made it possible to increase the speed of calculations, as well as reduce the probability of a search error and significantly improve the accuracy of the algorithm. The method of matching patterns makes it possible to find the necessary area on the map with almost 100 % correspondence, which will allow it to be used as a component of the navigation system of an unmanned aerial vehicle in conditions of active radio-electronic countermeasures.
***Keywords**: positioning algorithm, navigation system, monitoring, aerial photography.*

Безпілотні системи довели свою ефективність, але залишаються проблеми їх покращення та модифікації, що полягають в збільшенні часу польоту, дальності керування і передачі інформації по каналах зв'язку з наземними пунктами управління у необхідній кількості, із заданою швидкістю. Дана задача розв'язується шляхом збільшення пропускної здатності і завадостійкості каналів передачі інформації, що може бути досягнуто завдяки зосередження на борту максимуму пристроїв, які працюють в програмному режимі без постійного обміну інформацією з пунктом управління.

Орієнтування на місцевості безпілотного літального апарату зазвичай реалізується за допомогою систем супутникового зв'язку GPS, які, однак, при деяких умовах можуть працювати нестабільно. Перспективним рішенням проблеми орієнтації на місцевості в умовах відсутності сигналу супутникової навігаційної системи є застосування алгоритму позиціонування на місцевості без застосування супутникових систем зв'язку GPS. Розроблено та реалізовано новий алгоритм позиціонування, в якому для пошуку елементу зображення на карті місцевості використано метод знаходження відповідності шляхом створення паттернів, що дозволило підвищити швидкість виконання розрахунків, а також зменшити вірогідність похибки пошуку та значно покращити точність роботи алгоритму. Метод зіставлення паттернів надає змогу знайти необхідну місцевість на карті майже у 100 % відповідності, що дозволить *використовувати в якості складової навігаційної системи безпілотного літального апарату в умовах активної радіоелектронної протидії.*

***Ключові слова**: алгоритм позиціонування, навігаційна система, моніторинг, аерофотозйомка.*

Problem's Formulation

Unmanned aerial vehicles (UAVs) are widely used in military affairs, emergency monitoring, geodesy and cartography. UAVs of the armed forces are capable of conducting reconnaissance activities, scanning the airwaves, and conducting aerial photography. UAVs, which are equipped with weapons, can conduct combat operations against the enemy under the command of operators from the ground, destroying the infrastructure, equipment, and manpower of the enemy.

Purpose of combat UAVs:

– creation of an effective system of knowledge of goals;

– development of a reliable and fail-safe communication system between manned and unmanned aerial vehicles;

– creation of an on-board system for processing received information with subsequent selection of unnecessary or secondary information;

– development of a filtering device that will allow a group of UAVs to independently distribute targets among themselves, choosing among them the most important ones and planning a flight according to the environment, promptly responding to emerging external threats.

The civilian sphere of application of UAVs is just as diverse: from agriculture and construction to the oil and gas sector, as well as in scientific organizations, advertising companies, and mass media.

Purpose of civilian UAVs:

– observation of various objects, collection of measurements and other information;

– control of maritime shipping;

– environmental control;

– presentations, advertising, entertainment, creativity;

– delivery of goods by air;

– repair work, refueling/recharging at hard-to-reach objects and remote autonomous devices (weather stations, lighthouses, etc.);

– spraying of chemicals and application of fertilizers in the fields;

– support of climbers, tourists, expeditions with products, burners, spare parts, etc.; evacuation measures);

– retransmission of radio signals in order to increase the range of communication channels; generation or reflection of a laser beam;

– management of the behavior of living objects: movement of herds of horses, flocks of sheep; scaring away flocks of birds from airfields.

Analysis of recent research and publications

According to literary sources [1], unmanned systems have proven their effectiveness, but there are still problems with improving image processing technologies and infrastructure.

According to the authors [2], a very important problem is the task of ensuring the transmission of information through communication channels between the UAV and the ground control point in the required amount, at a given speed, and without distortion. This task is solved by increasing the bandwidth and immunity of information transmission channels, which can be achieved by concentrating on board the UAV a maximum of devices that work in software mode without constant information exchange with the control point. But at the same time, another problem may arise — the vulnerability of the data transmission channels between UAVs and their control point, which is solved by closing communication lines, using autonomous UAVs, and using satellite repeaters.

UAVs, which are used for military and civilian purposes, usually require improvement and modification, which, according to [3], consists of increasing the flight time, control range, and transmission of video images to the operator.

The increase in flight time is achieved by replenishing the UAV's energy reserves, which is achieved by increasing the volume of fuel, and, accordingly, by increasing the weight of the UAV.

However, it should be noted that an increase in the weight of a UAV within 20 % of its initial weight usually affects the flight performance without harming the application and durability [4]. Further weight increase negatively affects all aspects of UAV use, worsening its technical condition.

Amplification of the control signal of the UAV is achieved by installing more powerful antennas for the radio signal and hardware amplifiers of the radio signal, both on the UAV and on its control panel.

Orientation on the terrain of UAVs today is usually implemented using GPS satellite communication systems, which, however, can work unstable under some conditions. A promising solution to the problem of orientation on the terrain in the absence of a satellite navigation system signal is the use of a photo or video camera and the use of technical vision methods [5].

Formulation of the study purpose

The purpose of this work is to create an algorithm for UAV positioning on the terrain without the use of GPS satellite communication systems. This algorithm will allow the UAV to navigate the terrain, having only a terrain map (satellite image) and a camera on board. This algorithm can also be applied to UAVs with GPS satellite communication systems under conditions if the UAV has lost contact with the satellite.

Presenting main material

The navigation algorithm works as follows: an image from a UAV is loaded, its central part is rotated and cut, and the dimensions are subsequently reduced to $N \times N$ (for example, 64×64, 32×32, 16×16 pixels), the image is scaled to the size of a terrain map, which is presented in the form of a data matrix, after which the movement of the UAV will take place according to this data array, which facilitates the task of orientation on the terrain.

High-frequency images provide detail, and low-frequency images provide image structure. At the same time, the map should be reduced in size for detailing and reducing the number of pixels, which will speed up the time of determining the location and eliminate the error of the flight angle and height.

After the area map has been reduced in size, the pixel with the highest and the lowest RGB value (RGB is an additive color model that describes the way color is synthesized) is located according to the formulas:

$$RGB_{MAX} = \frac{Red_{MAX}+Green_{MAX}+Blue_{MAX}}{3}, \quad (1)$$

$$RGB_{MIN} = \frac{Red_{MIN}+Green_{MIN}+Blue_{MIN}}{3}, \quad (2)$$

where *Red, Green, and Blue* take values from 0 to 255 values.

That is, the value 255 corresponds to white, and 0 to black. Knowing the maximum and minimum values, it is possible to determine the threshold relative to which the information will be further coded according to the formula:

$$RGB_T = \frac{RGB_{MIN}+RGB_{MAX}}{2}. \quad (3)$$

After that, a matrix is created, which has the dimensions of the number of pixels corresponding to the image of the reduced map. This matrix is filled in such a way that if a pixel is less than the value of RGBT, then 1 (i.e. black) is entered, if it is more, then 0 (i.e. white). Thus, we have an image matrix from a binary code. To reduce the array, you can convert the binary code to hexadecimal. After the UAV picture is taken, it must be scaled down to a scale equal to the scale of the terrain map.

For the UAV picture to be found on the terrain map, it must be oriented to the east relative to the terrain map. To do this, it is suggested to cut out the central part of the picture, so that the cut square is oriented to the east. The cut-out square must be inscribed in a circle whose diameter is equal to the height of the UAV photo, that is, its smallest side. The side of the cut square can be calculated using the formula:

$$b = \frac{H}{\sqrt{2}}. \quad (4)$$

The location of the cutout center can be calculated using the following formulas:

$$OW = W/2,\ OH = H/2.$$

Thanks to the digital compass, which is on board the UAV, you can turn the picture to an angle that is oriented to the east and cut the desired fragment. After cropping the oriented part of the image, the dimensions are reduced so that this cropped square is $Npix \times Npix$ pixels. Thus, the map size reduction factor will be equal to the following value:

$$k_m = \frac{N_{pix}}{b}. \tag{5}$$

where $Npix$ is 8, 16, 64, 128.

Of course, the best option would be 64, as detail is preserved, and the speed of processing remains rational [6].

The transformation of this part into binary or hexadecimal code is implemented in the same way as when processing a terrain map using the RGBT value. In order to be able to navigate during the day, RGBT can be reduced or increased, depending on the lighting.

The search for a picture on the terrain map is carried out by the vector method, namely, through the cosine of the angle between two vectors. If the cosine of the angle approaches unity, it means that the UAV is most likely in the given location. The search formula will look like this:

$$\cos(\bar{a}, \bar{b}) = \frac{\bar{a} \cdot \bar{b}}{|\bar{a}| \cdot |\bar{b}|} = \frac{a_1 b_1 + a_2 b_2 + \cdots + a_n b_n}{\sqrt{a_1^2 + a_2^2 + \cdots + a_n^2} \cdot \sqrt{b_1^2 + b_2^2 + \cdots + b_n^2}}, \tag{6}$$

where $a1$, $a2. . . an$ is the value of the code in the cell of the map matrix, $b1$, $b2. . . bn$ is the value of the code in the cell from the UAV image matrix.

The Hamming distance is used to determine the location of the UAV. The Hamming distance is the number of positions in which the corresponding symbols of two words of the same length are different [7]. In a more general case, the Hamming distance is used for strings of the same length of any alphabets and serves as a difference metric (a function that determines the distance in metric space) of objects of the same size.

To determine the location of the UAV, the place where the number of errors is the smallest in all rows and columns is selected.

The process of obtaining data for search consists of the following steps:

– obtaining a 15000×7000 map image in .BMP format (Fig. 1);

– creation of a temporary place in the memory for the image in shades of gray (IMAQ block) (Fig. 2, 3);

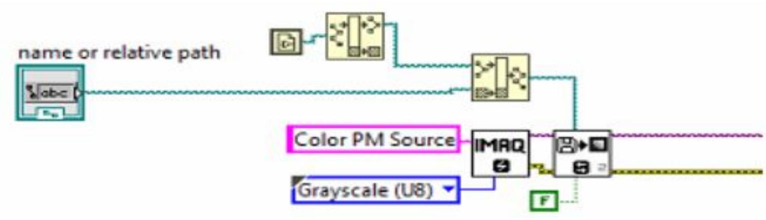

Fig. 1. Algorithm for obtaining a map image

– receiving a 1399×720 video file in AVI format with the creation of a temporary place in the memory for a color image (RGB U32) and in shades of gray (Grayscale U8) for converting the image into a pattern (Fig. 4);

– conversion of a color video frame to an image in shades of gray.

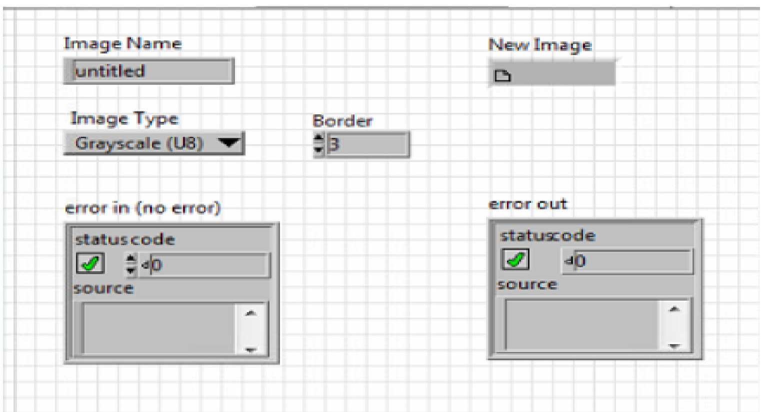

Fig. 2. Display panel of the temporary memory allocation algorithm

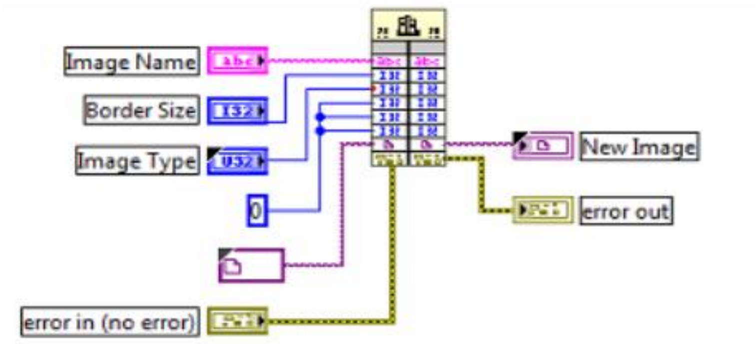

Fig. 3. The algorithm for creating a temporary place in memory

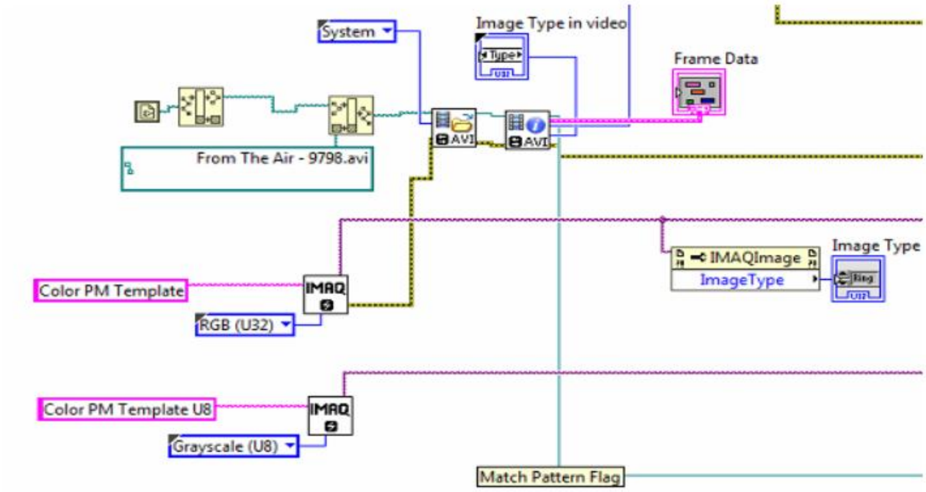

Fig. 4. The algorithm for obtaining a video image

Converting a color image to grayscale is necessary to speed up its processing and enable the algorithm to function at different times of the year. At the same time, finding the correspondence of the image with the map will depend only on shades of gray, and not on all colors. Also, an image in shades of gray requires less space in the UAV's memory than a color one, so the UAV can navigate on a larger gray map than in the color version.

The algorithm for converting color frames from video in shades of gray is presented in Fig. 5. Pattern matching allows you to quickly identify areas of grayscale images that match a known reference pattern, called a model or template. Pattern matching involves creating a pattern that represents the object you are looking for. The machine vision program then searches for instances of the pattern in each resulting image, computing a score for each match. Through pattern matching, one can observe the pattern match under varying degrees of illumination, blur, noise, and geometric transformations such as shifting, rotating, or scaling the pattern.

When creating a pattern image description to search during the pattern matching phase, the description data is appended to the input pattern image. During the matching phase, the pattern descriptor is extracted from the pattern image and used to find the pattern in the verification image. Low Discrepancy Sampling algorithm was selected for machine vision training, the display panel of which and the training algorithm itself are presented in fig. 6 and 7, respectively.

At the same time, a sampling algorithm with low discrepancy was used. This algorithm extracts the most important information for the representation of the image, namely, the data about the lighter and darker points, as well as the transitions between them in shades of gray, are taken from the image.

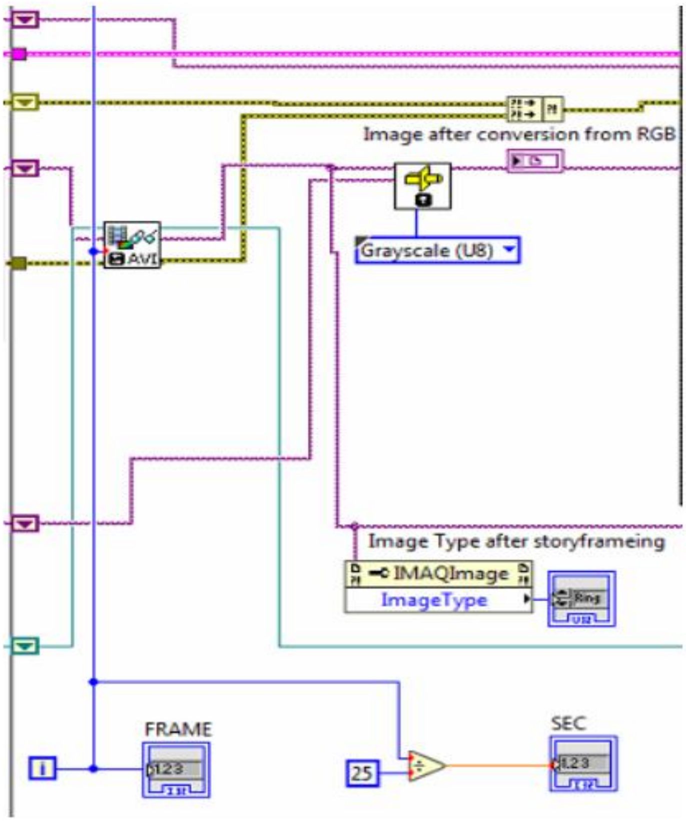

Fig. 5. Algorithm for converting color frames from video in shades of gray

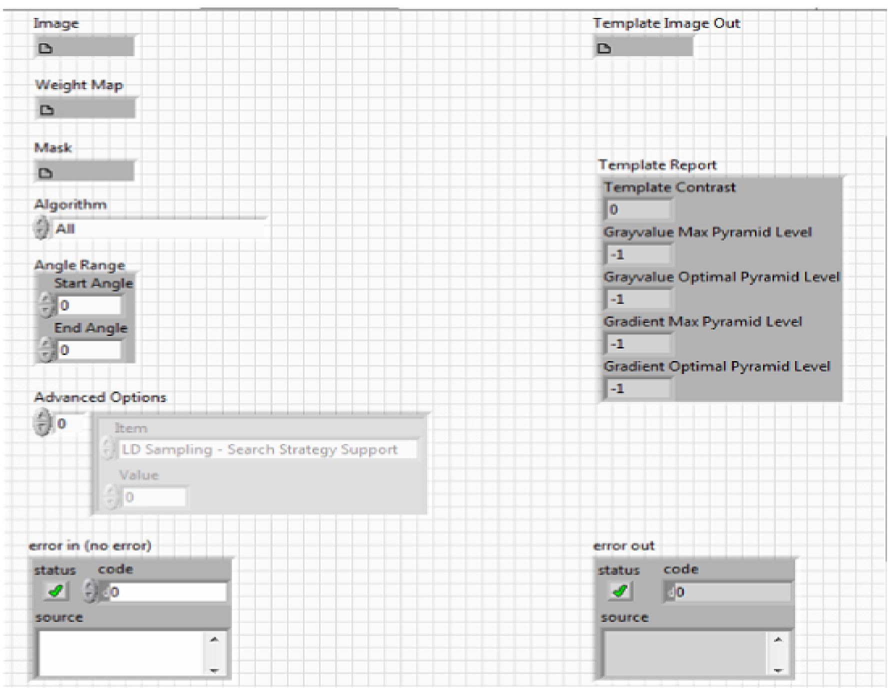

Fig. 6. Machine vision learning algorithm display panel — Low Discrepancy Sampling

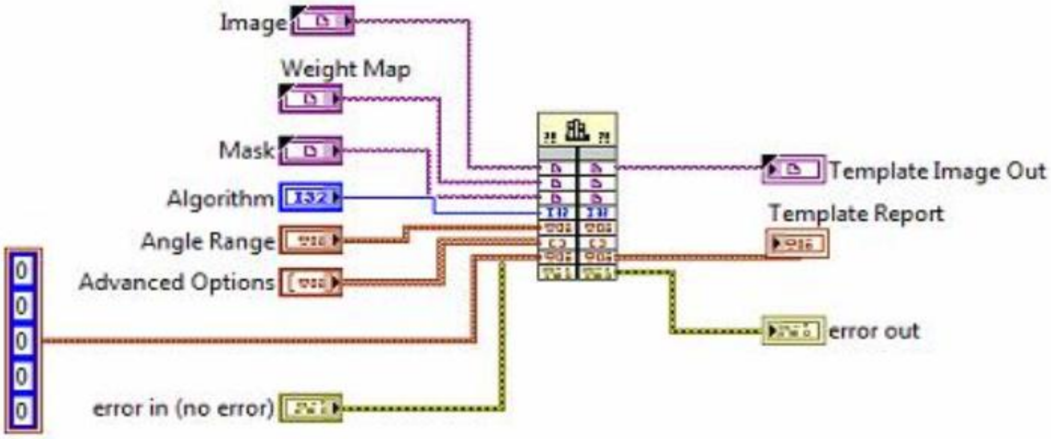

Fig. 7. Machine vision learning algorithm - Low Discrepancy Sampling

When applying the image search algorithm on the map, each video frame, after being converted into a pattern and undergoing machine vision training, is sent to the search algorithm. The search algorithm (Fig. 8) includes three parts:

– correspondence of the created pattern with the image on the map;
– displaying the found fragment on the map with a red rectangle;
– record coordinates in the data array.

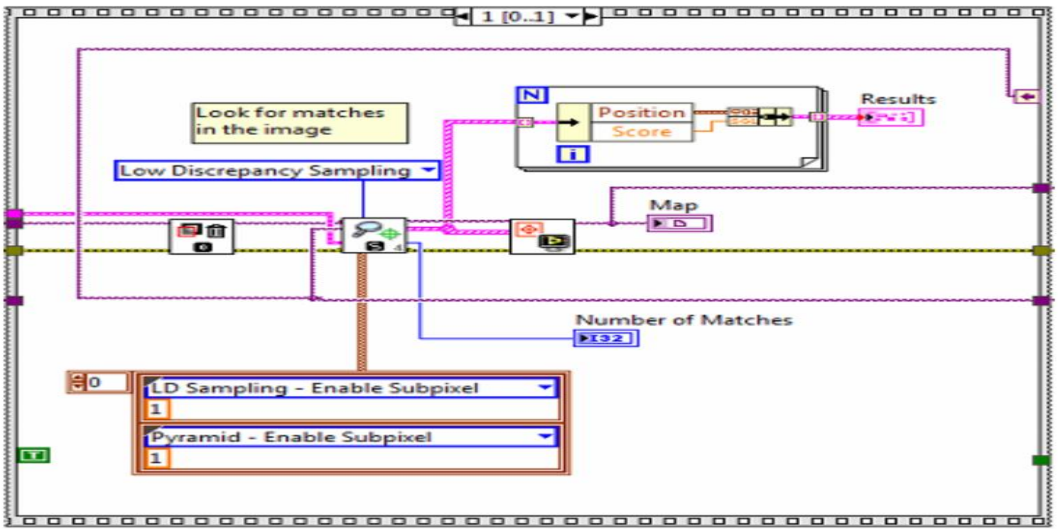

Fig. 8. Algorithm for searching the created template on the map

The created pattern is first searched with 100 % correspondence with the image on the map, if a complete correspondence is not found, then the search is carried out on the lightest and darkest points and gray gradient transitions between them. To visually confirm the correct operation of the algorithm, the found fragment is displayed on the map with a red rectangle (Fig. 9).

The main panel of the algorithm display is necessary for the operation of the UAV operator to set the initial coordinates, the route and load the map of the required terrain before the flight, as well as to check the operation of the algorithm and its calibration.

The main panel displays the following items.

1. Video frames after processing from a color image to shades of gray (Image after conversion from RGB to Grayscale).

2. Frames from the video after learning machine vision and creating a pattern (Image after learning).

3. Created template (pattern) for searching on the map (Template).
4. Image of the map with markings of the found fragments (Map).
5. Array with the coordinates of the found fragment on the map (Results).
6. Error display blocks (error after learning, error after comparison).

To demonstrate the operation of the algorithm, a video of a UAV flight with vertical shooting was chosen (Fig. 10).

Since it is impossible to find the area from the selected video on the map and measure the height, the example of the area map was made by hand. For this video, every first frame of a second was selected. After that, the frames were placed on the substrate, the size of 15000×7000 pixels, in the form of an indirect route.

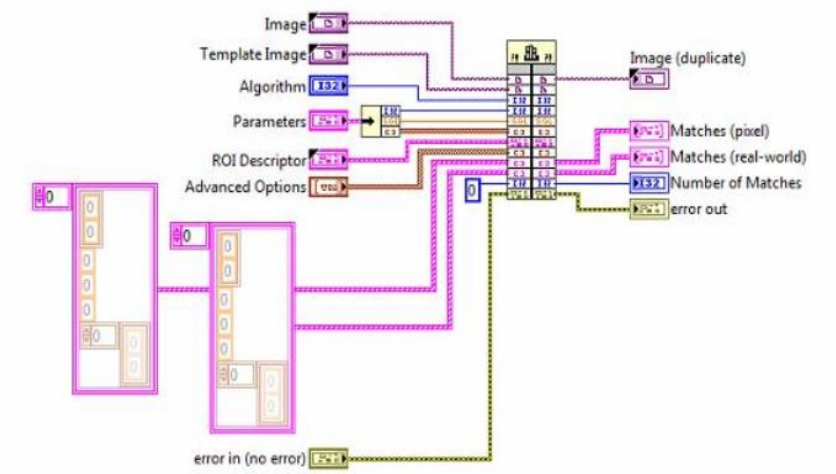

Fig. 9. Algorithm for finding correspondences

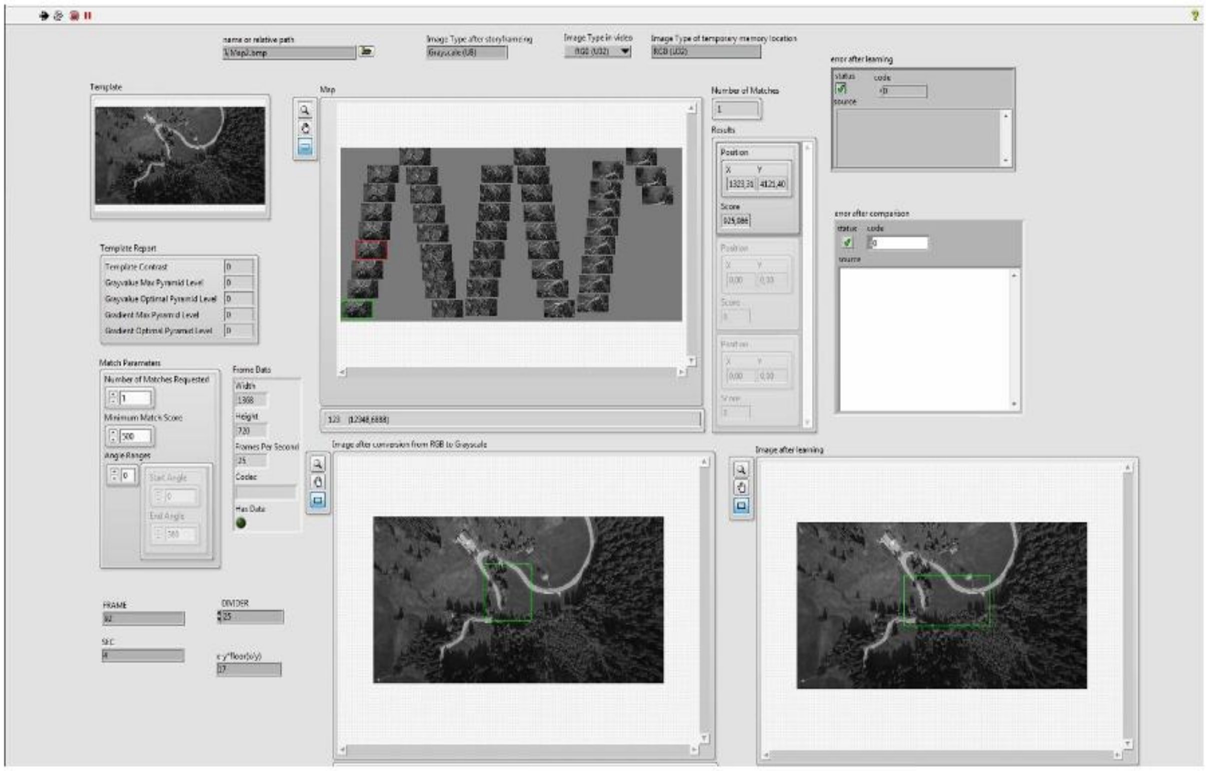

Fig. 10. The main algorithm display panel

Conclusions

1. A computer vision algorithm was developed and implemented to establish the correspondence of video frames received from aboard a UAV during flight to fragments of an existing map depicting the terrain.

2. A new UAV positioning algorithm was developed and implemented using the obtained images, in which the method of finding correspondence by creating patterns was used to search for an image element on a terrain map, which allowed to increase the speed of calculations, as well as reduce the probability of a search error and significantly improve the accuracy of the algorithm .

3. The pattern matching method makes it possible to find the required area on the map with almost 100 % matching, which makes this method more accurate than the matrix and others.

4. The results of the research can be used as a component of the UAV navigation system, which will ensure the operation of such a system in conditions of loss of the signal of the global satellite navigation system or conditions of active radio-electronic countermeasures.

References

[1] Rostopchyn V.V., BurdunI. E. (2016). Bezpilotni aviacijni systemy: osnovni ponjattja [Unmanned aerial systems: basic concepts] *ELEKTRONIKA: Nauka, Tekhnologhija, Biznes. - ELECTRONICS: Science, Technology, Business. series. 7, (pp.82-88).* [in Ukrainian].

[2] Saljnyk Ju.P., MatalaI. V.(2013). Analiz tekhnichnykh kharakterystyk i mozhlyvostej bezpilotnykh aviacijnykh kompleksiv operatyvno-taktychnogho ta taktychnogho radiusa diji armij rozvynenykh krajin [Analysis of the technical characteristics and capabilities of unmanned aerial systems of operational and tactical range of armies of developed countries] *Vijsjkovotekhnichnyj zb.. series. 7, (pp.70-74).* [in Ukrainian].

[3] Zbrutsky O.V., Masko O.M., Sukhov V.V. (2012). Bezpilotni litaljni aparaty kontejnernogho startu: suchasnyj stan i naprjamky doslidzhenj. [Container launch unmanned aerial vehicles: current status and research directions] *Visnyk. National technical "KPI" University of Ukraine: "Mechanical Engineering" series. 62, (pp.63-66).* [in Ukrainian].

[4] Shapovalov O.L Kolesnyk., D.M., Bolotov Gh.P., Zhurakhov O.V. (2018). Analiz konstruktyvnykh osoblyvostej i tekhnichnykh kharakterystyk osnovnykh typiv sylovykh ustanovok dlja bezpilotnykh litaljnykh aparativ. [Analysis of design features and technical characteristics of the main types of power plants for unmanned aerial vehicles.] *Tekhnichni nauky ta tekhnologhiji., series. 2(8), (pp.57-65).* [in Ukrainian].

[5] Ilyushko V.M., Mitrahovich M.M., Strelnikov V.I. (2020). Modeli ta metody zabezpechennja funkcionaljnoji stijkosti vymirjuvaljnykh pidsystem avtonomnogho maloghabarytnogho litaljnogho aparata [Models and methods for ensuring the functional stability of measuring subsystems of an autonomous small-sized aircraft] *dys. ... kan. tekhn. nauk : 05.13.03 / Nac. aerokosm. un-t. im M. Je. Zhukovsjkogho «Kharkiv. aviac. in-t». – Kharkiv. 22* [in Ukrainian].

[6] Szeliski R. (2022) Structure from motion and SLAM. In: Szeliski R (ed) Computer vision: algorithms and applications. Springer International Publishing Cham, *(pp.* 543–594). https://doi.org/10.1007/978-3-030-34372-9_11.

[7] Ed Dowring (2015) Fundamentals of Machine Vision with NI myRIO. *Department of Electrical and Computer Engineering, Rose-Halman Institute of Technology.*

Список використаної літератури

1. Ростопчин В.В., Бурдун І.Е. Безпілотні авіаційні системи: основні поняття. ЕЛЕКТРОНІКА: Наука, Технологія, Бізнес. 2016. № 7. 82–88.
2. Сальник Ю.П., Матала І.В. Аналіз технічних характеристик і можливостей безпілотних авіаційних комплексів оперативно-тактичного та тактичного радіуса дії армій розвинених країн. Військовотехнічний зб. 2013. № 7. 70–74.

3. Збруцький О.В., Масько О.М., Сухов В.В. Безпілотні літальні апарати контейнерного старту: сучасний стан і напрямки досліджень. Вісник. Нац. техн. унів-ту України «КПІ» : серія «Машинобудування». 2012. № 62. 63–66.
4. Аналіз конструктивних особливостей і технічних характеристик основних типів силових установок для безпілотних літальних апаратів / О.Л. Шаповалов, Д.М. Колесник, Г.П. Болотов, О.В. Журахов // Технічні науки та технології. 2018. № 2(8). 57–65.
5. Жежера І.В. Моделі та методи забезпечення функціональної стійкості вимірювальних підсистем автономного малогабаритного літального апарата : дис. … кан. техн. наук : 05.13.03 / Нац. аерокосм. ун-т. ім М.Є. Жуковського «Харків. авіац. ін-т». – Харків, 2020. 22.
6. Szeliski R. (2022) Structure from motion and SLAM. In: Szeliski R (ed) Computer vision: algorithms and applications. Springer International Publishing Cham, 543–594. https://doi.org/10.1007/978-3-030-34372-9_11
7. Ед Доурінг. Основи машинного зору з NI myRIO. Департамент електротехніки та обчислювальної техніки. *Технологічний інститут Роуз-Халман*. 2015. 166.

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