УДК 621.327:681.5

SOFTWARE AND HARDWARE MODULE FOR AUTOMATED DETECTION AND RECOGNITION OF INTEREST OBJECTS TO INCREASE THE LEVEL OF PROCESSING EFFICIENCY AND RELIABILITY OF AERIAL RECONNAISSANCE DATA

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DOI: 10.15673/atbp.v16i1.2773

Abstract. *The requirements for the air reconnaissance system using unmanned aircraft systems are being studied. Problematic aspects of the air reconnaissance data processing process are analyzed from the point of view of ensuring the required level of operational efficiency and reliability of intelligence information. The possibility of automating the process of detecting aerial reconnaissance objects on video images is being investigated. A software-hardware module for automated detection and recognition of objects of interest is being developed to increase the level of processing efficiency and reliability of air reconnaissance data. Modern models of detection and recognition of objects of interest based on algorithms of the YOLO platform are studied. The software component of the module is being developed using the YOLOv8 algorithm architecture and a set of data formed in the conditions of air reconnaissance. The analysis of the results of experimental studies shows that: the developed model allows to ensure the required level of operational efficiency of video image processing and the reliability of aerial reconnaissance data; practical implementation of the developed model at ground command and control stations is possible without the use of additional computing equipment. The hardware component of the module is being developed using Raspberry Pi components. The analysis of quantitative evaluations of the efficiency of data processing using the developed software and hardware module on board the UAV of the studied class indicate an increase in time delays compared to the implementation at the command-and-control station, but it allows to ensure the required level of reliability. Further scientific research will be aimed at investigating the peculiarities of the implementation of the conceptual foundations of the developed module for various classes of UAV in order to increase the level of processing efficiency and reliability of aerial reconnaissance data.*

Анотація. *Досліджуються вимоги до системи повітряної розвідки з використанням безпілотних авіаційних систем. Аналізуються проблемні аспекти процесу обробки даних повітряної розвідки з позиції забезпечення необхідного рівня оперативності та достовірності розвідувальної інформації. Досліджується можливість автоматизації процесу виявлення об'єктів повітряної розвідки на відеозображеннях. Розробляється програмно-апаратний модуль автоматизованого виявлення та розпізнавання об'єктів інтересу для підвищення рівня оперативності обробки та достовірності даних повітряної розвідки. Досліджуються сучасні моделі виявлення та розпізнавання об'єктів інтересу на базі алгоритмів платформи YOLO. Розробляється програмна складова модуля з використанням архітектури алгоритмів YOLOv8 та набору даних, сформованих в умовах ведення повітряної розвідки. Аналіз результатів експериментальних досліджень свідчать про те, що: розроблена модель дозволяє забезпечити необхідний рівень оперативності обробки відеозображень та достовірності даних повітряної розвідки; практична реалізація розробленої моделі на наземних станціях керування та контроля можлива без використання додаткового обчислювального обладнання. Розробляється апаратна складова модуля з використанням компонентів Raspberry Pi. Аналіз кількісних оцінок оперативності обробки даних з використанням розробленого програмно-апаратного модуля на борту безпілотних літальних апаратів досліджуваного класу свідчить про зростання часових затримок у порівнянні з реалізацією на станції керування та контролю, проте дозволяє забезпечити необхідний рівень достовірності. Подальші наукові дослідження будуть спрямовані на дослідження особливостей реалізації концептуальних засад розробленого модуля для різних класів безпілотних авіаційних систем з метою підвищення рівня оперативності обробки та* *достовірності даних повітряної розвідки.*

Keywords: *unmanned aircraft system, aerial reconnaissance data, video images, object of interest, hardware and software module, reliability, responsiveness, recognition.*

Ключові слова: *безпілотна авіаційна система, дані повітряної розвідки, відеозображення, об'єкт інтересу, програмно-апаратний модуль, достовірність, оперативність, розпізнавання.*

1. Introduction

The experience of hostilities on the territory of Ukraine shows the active use of unmanned aerial systems (UAS) both by units of the defense forces and by the enemy [1-4]. At the same time, it should be noted that both domestically produced anti-aircraft missiles and those provided from the first days of the war by partner countries are used for reconnaissance and strike purposes [5, 6]. However, to date, the use of UAS is associated with the presence of a number of problematic factors that have a significant impact on the effectiveness (success) of the combat mission. Thus, the experience of using reconnaissance UAS by units of the security and defense sector shows the dependence of the efficiency of decryption of air reconnaissance data (ARD) and the reliability of the decryption results on the professional abilities of the operator of the target load and the physiological abilities of the human visual system. This is due to the lack of means (tools) for automating the processes of processing and decoding ARD both on board unmanned aerial vehicles (UAV) and at ground command and control stations (CCS) [1, 6].

In turn, a characteristic feature of the enemy in the field of anti-aircraft defense is the dynamic implementation of modern progressive technologies and testing their effectiveness in combat conditions [7, 8]. Thus, among the extreme innovations of the enemy, it should be noted the use of computer vision technologies, which allow to provide conditions for increasing the level of operational intelligence processing and the reliability of ARD [8]. At the same time, it should be noted that this trend is observed for UAS of all classes, that is, from FPV drones (actively used on the lines of combat collision) to UAS of the operational-tactical class [9, 10].

Thus, to date, the advantage of the enemy in the digitalization of the intelligence and information space is observed, which leads to the need to find new approaches and transform the process of processing and deciphering air reconnaissance data.

Therefore, the goal of the work is the development of a software and hardware module for the automated detection and recognition of aerial reconnaissance objects to increase the level of processing efficiency and reliability of aerial reconnaissance data.

2. Literature analysis

The analysis of the latest scientific researches shows that nowadays compression technologies are actively used to ensure the necessary level of operational efficiency of data processing generated by the sensors of the air reconnaissance system at the UAS [11-13]. This is due to the need for a compact presentation of encoded ARD to overcome the imbalance between vol'capacity of transmitted intelligence data and bandwidth of video data transmission lines (data link). For this purpose, separate processes (stages) of video image processing implemented in the JPEG platform are being actively improved. This is due to the fact that most of the sensors of the target equipment of the UAS form intelligence information in this data compression format [5, 6, 10]. However, the disadvantage of using algorithms of the above-mentioned family is low resistance to errors in video data transmission lines, which can lead to significant distortion and destruction of video images and, as a result, to the impossibility of further decryption of ARD [11, 13]. Thus, the use of the specified algorithms does not allow to ensure the required level of reliability of intelligence information received from UAS. The analysis of sources [14-15] shows that to solve the above-mentioned problem, the use of a two-hierarchical scheme of statistical coding of data is proposed, that is, the transformation of the Huffman statistical coding process into a two-stage implementation using marker separators. This makes it possible to ensure the required level of reliability of ARD and a more profitable (compact) presentation of data generated by on-board sensors [15].

In turn, the automation of the video image processing process today is closely related to the use of OpenCV computer vision libraries, which have a fairly large functionality for processing and evaluating video data. So today, the synthesis of computer vision technologies and deep machine learning based on artificial neural networks has made it possible to implement the process of automating the detection, segmentation and classification of objects of interest [16-23]. The analysis of sources [16, 20] shows that the implementation of the specified approach allows for automated tracking of vehicle traffic on busy road sections, parking lots, and other urban infrastructure facilities. In turn, the analysis of sources [16, 23] indicates the active use of technologies for detecting and recognizing license plates of vehicles and the faces of offenders in the system of situational centers of law enforcement agencies for prompt response to offenses.

In this regard, in order to increase the level of processing efficiency and reliability of air reconnaissance data, it is proposed to investigate the possibility of developing a software and hardware module for the automated detection and recognition of aerial reconnaissance objects based on computer vision technologies, deep machine learning, and artificial neural networks.

3. Object, subject, and methods of research

For developmentof the software and hardware module (SHM) of the automated detection and recognition of aerial reconnaissance objects (ARO) in the aerial reconnaissance system using UAS, it is necessary to form partial tasks that need to be solved:

1. To investigate the tools (technologies) of computer vision for the automated processing of video images formed by the on-board sensors of the UAS target equipment.

2. Investigate existing algorithms based on deep machine learning and artificial neural networks to ensure automation of the process of detecting aerial reconnaissance objects.

3. To develop an algorithm for automated detection and recognition of ARO (software component of the module) taking into account the requirements for the tasks of the air reconnaissance system.

4. Investigate the possibility and tools for further integration of the developed algorithm in UAS. At the same time, it is necessary to determine the area of integration - an unmanned aerial vehicle or a command and control station.

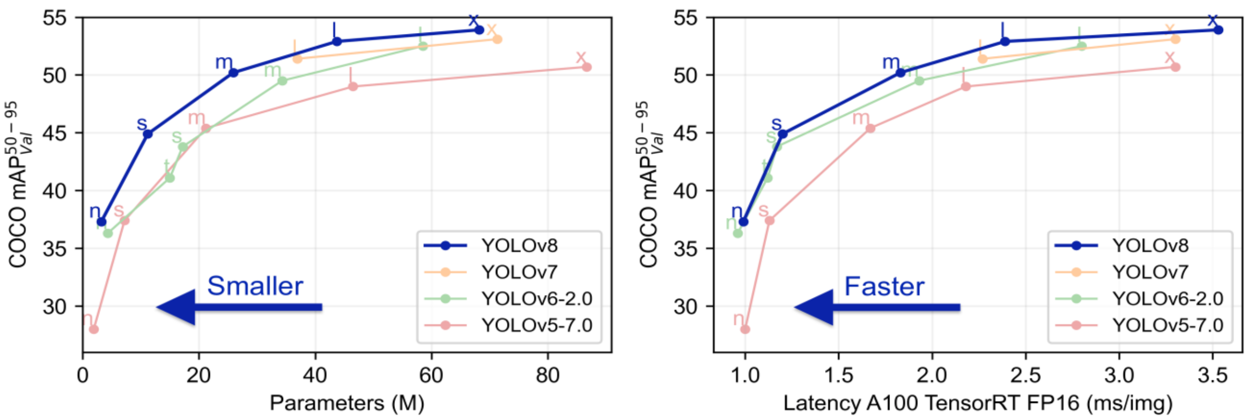
5. Develop the hardware part of the module taking into account the requirements for computing and energy capacities.

6. Evaluation of the effectiveness of SHM automated detection and recognition of aerial reconnaissance objects according to the following quantitative estimates:

- to assess the efficiency of processing video images generated by on-board sensors, it is suggested to use the following quantitative assessment: T_{proc}^{VF} is video frame (video image) processing time;

- to assess the reliability of air reconnaissance data, it is proposed to use the following quantitative assessment: P_{od}^{VF} - the probability of detection (recognition) of aerial reconnaissance objects on the video frame (video image).

To solve the first two partial tasks, it is proposed to investigate the algorithms of the YOLO family, which are quite actively developing (dynamic transformation from the first to the eighth versions) [24]. These algorithms are used in many directions (detection, recognition, segmentation, classification, posture determination) due to the possibility of balancing between efficiency and accuracy indicators (Fig. 1) [25].



a) *b)*

Fig. 1. Comparative analysis of algorithms of the YOLO v5-8 family: a) by accuracy and algorithmic complexity; b) by efficiency (time delays for video image processing) Source: a), b) [25]

Рис. 1. Порівняльний аналіз алгоритмів сімейства YOLO v5-8: а) за точністю та алгоритмічною складністю; б) за ефективністю (часові затримки обробки відеозображення) Джерело: а), б) [25]

The analysis of the data shown in Fig. 1 shows that today the YOLO algorithms version 8 have gains compared to their predecessors in the following indicators:

- accuracy of detection of objects of interest (Fig. 1.a));
- algorithmic complexity, that is, the number of parameters used in the process of model training (Fig. 1.a));
- efficiency of data processing, i.e. it has shorter time delays compared to its predecessors (Fig. 1.b)).

The presence of the aforementioned advantages of YOLOv8 algorithms is evidenced by statistical data for the year 2023 regarding the training of models based on the studied algorithms, shown in Fig. 2 [26]. The analysis of the data shown in Fig. 2 shows that more than 15 million models were trained in 2023 alone, most of which are models for detecting objects of interest (almost 80%).

Thus, taking into account the results of the comparative analysis of the data shown in Fig. 1.a) - 1.b), it is proposed to use YOLOv8 algorithms for further development of the software part of the module for automated detection and recognition of ARO. The solution of the third partial task involves the development of an algorithm for automated detection and recognition of ARO (a software component of the module) taking into account the requirements for the tasks of the air reconnaissance system.

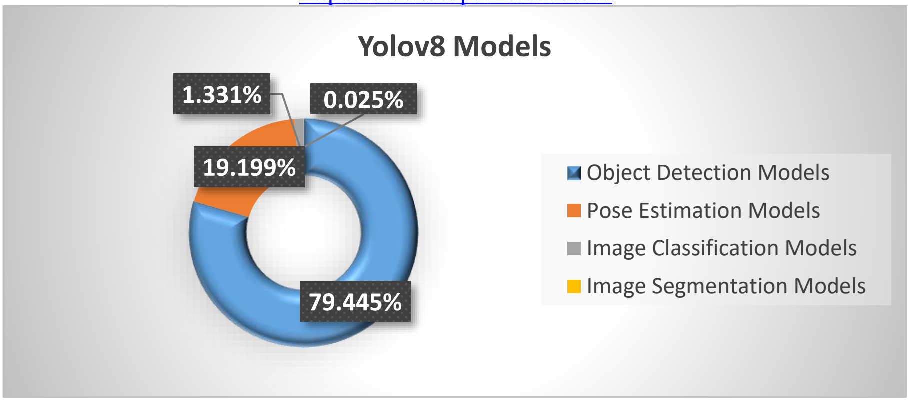


Fig. 2. Analysis of the number of trained models for 2023. Source: developed by the authors
Рис. 2. Аналіз кількості навчених моделей за 2023 рік. Джерело: розроблено авторами

For this purpose, it is proposed to use the concept proposed in works [27, 28], which provides for the formation of a data set according to the requirements of the air reconnaissance system for model training. The general scheme of the formation of the software component of the module of automated detection and recognition of ARO is presented in Fig.3.

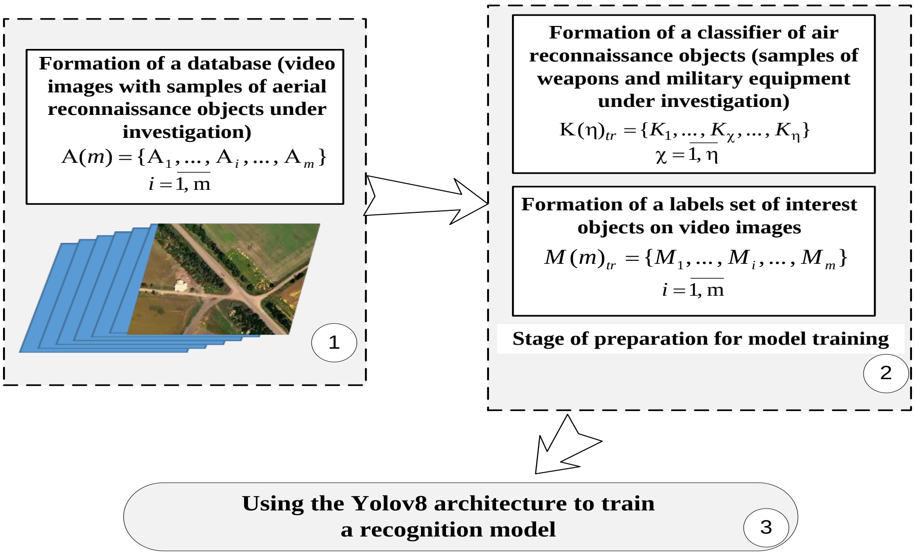


Fig. 3. General diagram of the formation of the software component of the module of automated detection and recognition of ARO. Source: developed by the authors
Рис. 3. Загальна схема формування програмної складової модуля автоматизованого виявлення та розпізнавання АРО. Джерело: розроблено авторами

The scheme shown in Fig. 3 includes the following components:

1. Formation of a data set (a set of video images) with objects that should be recognized by the automated model under development, taking into account the requirements for the tasks of the air reconnaissance system. The video data set used for training, in the general case is described by the following expression:

$$A(m)_{tr}=\{A_1,\ldots,A_i,\ldots,A_m\},\ i=\overline{1,m}, \quad (1)$$

Where $A(m)_{tr}$ is a set of video data (video images), $i=\overline{1,m}$;
m is the number of video images (that is the power of the set for training);
A_i is a video image of the data set $A(m)_{tr}$.

As a data set, for further training of the recognition model, it is suggested to use video images where the objects of interest are 2 classes:

First: samples of weapons and military equipment (includes types of light and heavy armored vehicles);

Second: personnel of military units (people in military uniform).

2. The stage of data preparation for training includes the following components:

- formation of the ARO classifier given by the following expression:

$$K(\eta)_{tr}=\{K_1,\ldots,K_\chi,\ldots,K_\eta\},\ \chi=\overline{1,\eta}, \quad (2)$$

Where $K(\eta)_{tr}$ is the classes set of ARO for detection in the video images set $A(m)_{tr}$, $\chi=\overline{1,\eta}$;

η is a number of classes of objects of interest that require recognition;

K_χ is a χ- th class of the set $\mathrm{K}(\eta)_{tr}$ of ARO.

Taking into account the above-defined requirements for the number of researched ARO, the strength of the classes set $\mathrm{K}(\eta)_{tr}$ will have the following form:

$$|\mathrm{K}(\eta)_{tr}| = 2,$$

Where $|\mathrm{K}(\eta)_{tr}|$ is the strength of the classes set $\mathrm{K}(\eta)_{tr}$ of ARO for detection in a set of video images $\mathrm{A}(m)_{tr}$;

- formation of a set of ARO labels on video images for further training of an artificial neural network. In general, a set of ARO labels in the video image A_i data set $\mathrm{A}(m)_{tr}$ is given by the following expression:

$$M(m)_{tr} = \{M_1, \dots, M_i, \dots, M_m\}, \; i = \overline{1, \mathrm{m}}, \quad (3)$$

Where $M(m)_{tr}$ is the set of ARO labels found in the data set $\mathrm{A}(m)_{tr}$, used to train the model, $i = \overline{1, \mathrm{m}}$;

M_i is the number of objects labels for the video image A_i.

3. The final stage of the formation of the software component of the automated detection and recognition of SHM is the use of the architecture of the YOLOv8 for training the recognition model, which is formed in the interests of the air reconnaissance system (Fig. 4) [29].

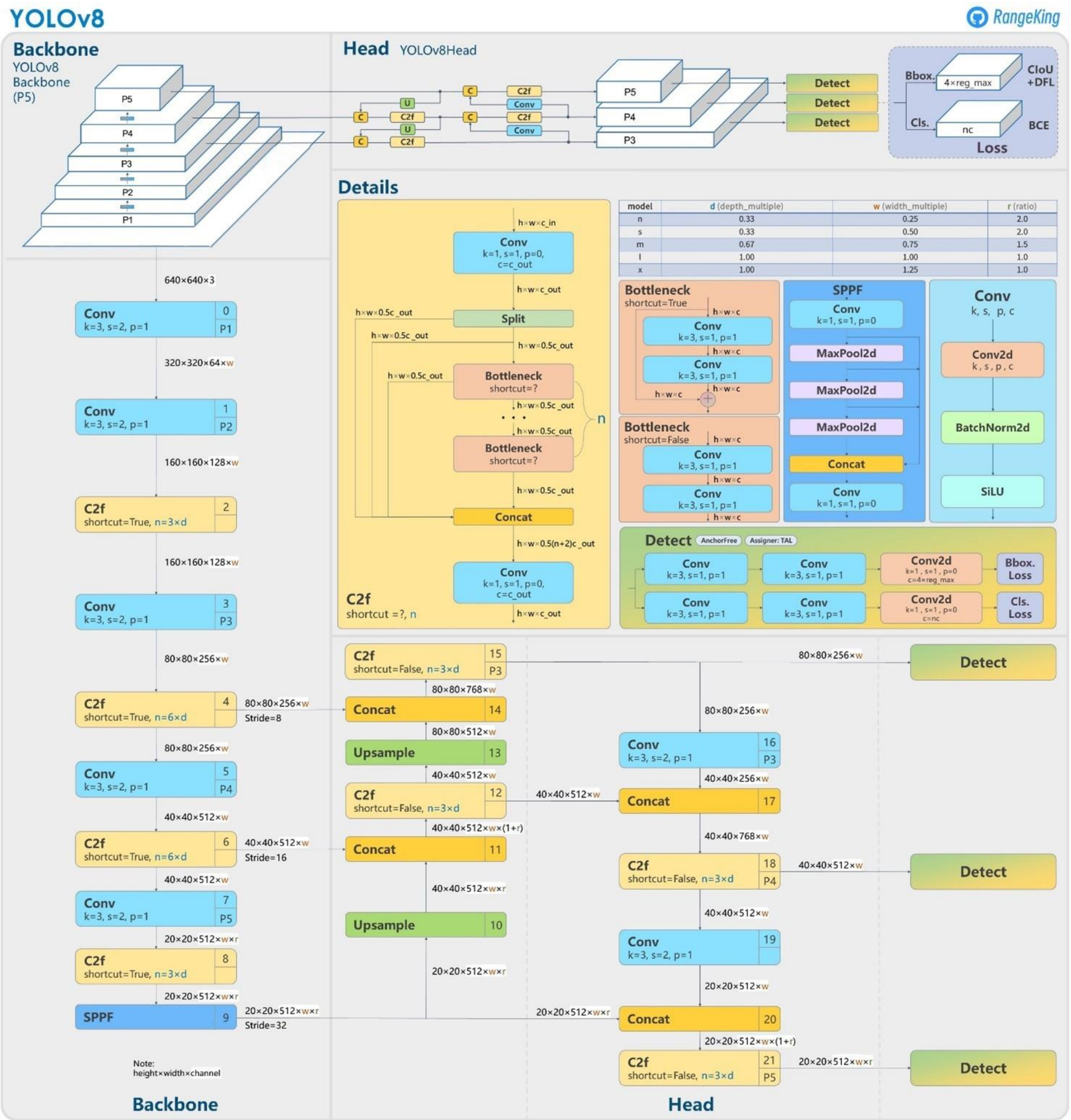


Fig. 4. Structural sheme of the detection modelobjects of YOLOv8 algorithms. Source: a), b) [29]
Рис. 4. Структурна схема об'єктів моделі виявлення алгоритмів YOLOv8. Джерело: а), б) [29]

Quantitative evaluations of the results of the training of the developed software component of the module of automated detection and recognition of ARO are shown in Fig. 5. It should be noted that the dataset $\mathrm{A}(m)_{tr}$ is used to train the model, consisting of:

1. Service data:
- video images formed by tactical level UAS on-board sensors;
- video images obtained from FPV drones.
2. Data from open sources - video images from messengers and web sites.

The power of the data set $\mathrm{A}(m)_{tr}$, used for model training, is about 1000 video images, the training period is 100 epochs.

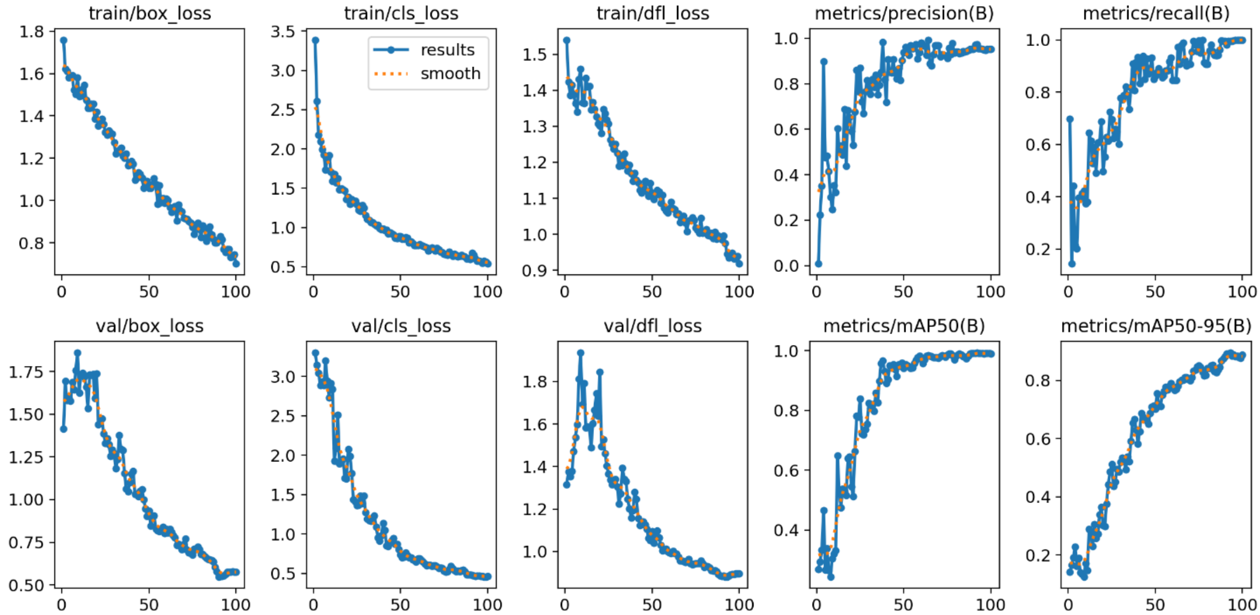


Fig. 5. Quantitative evaluations of the results of the training of the developed software component of the automated detection and recognition of ARO. Source: developed by the authors

Рис. 5. Кількісні оцінки результатів навчання розробленої програмної складової автоматизованого виявлення та розпізнавання АРО. Джерело: розроблено авторами

The following quantitative indicators were used to assess the effectiveness of the developed model from the point of view of ensuring the required level of reliability:

1. Precision (accuracy) - the proportion of correctly detected objects compared to the total number of objects in video images. For the developed model, the studied indicator has quite high results at the end of training periods and is about 97% (Fig. 5).
2. mAP (Mean Average Precision) is the average precision of the ARO detection model for the studied classes. For the developed model, the investigated indicator has the following values:

- mAP with a model confidence of 50% when approaching the hundredth epoch is 99% (Fig. 5);
- in turn, mAP with model confidence from 50 to 95% is about 89% (Fig. 5).

This indicates fairly high average accuracy results for the developed object recognition model.

Thus, the analysis of the quantitative estimates of the developed model shown in Fig. 5 indicates the creation of conditions for ensuring the necessary level of reliability of the ARD.

Next, it is proposed to evaluate the developed model to determine the level of efficiency of video data processing and its reliability.

4. Results

The evaluate of the developed model using test video images to determine the level of efficiency of video data processing and their reliability. For this purpose, it is necessary to form a set of test data (video images) that meets the requirements of the developed model, taking into account the features of the ARO in the air reconnaissance system. In the general casethe test data set is given by the following expression:

$$\mathrm{B}(\vartheta)_{test} = \{\mathrm{B}_1, \ldots, \mathrm{B}_j, \ldots, \mathrm{B}_\vartheta\},\ j = \overline{1, \vartheta}, \quad (4)$$

Where $\mathrm{B}(\vartheta)_{test}$ is a set of test video images, $j = \overline{1, \vartheta}$;

ϑ is a number of test video images;

B_j is the j - th video image of the data set $\mathrm{B}(\vartheta)_{test}$.

For experimental studies, a video information resource consisting of 1742 video images was used as the initial data, i.e.:

$$|B(\vartheta)_{test}| = 1742 \ ,$$

Where $|B(\vartheta)_{test}|$ is the power of the test set $B(\vartheta)_{test}$ (the number of video images B_j in the set $B(\vartheta)_{test}$).

In Fig. 6 shows examples of test video images B_j, receivedas a result of aerial reconnaissance using UAS of tactical class.

Fig. 6. Examples of reduced-size test video images obtained as a result of aerial reconnaissance using UAS of tactical class. Source: developed by the authors
Рис. 6. Приклади зменшених тестових відеозображень, отриманих у результаті повітряної розвідки з використанням БЛА тактичного класу. Джерело: розроблено авторами

Results of detection of AROs on test video images shown in Fig. 7.

Fig. 7. Examples of the results of using the developed software component of the recognition module of AROs. Source: developed by the authors
Рис. 7. Приклади результатів використання розробленої програмної складової модуля розпізнавання АРО. Джерело: розроблено авторами

The analysis of the data shown in Fig. 7 shows that the software component of the module under development, even in conditions of rather low quality of video images B_j, allows you to ensure the required level of reliability (accuracy of detecting objects of interest on video images). Even when quantifying the confidence of the model that the ARO of the studied class (weapons and military equipment) are present in the video images, which is equal to 0,59 and 0,63 (Fig. 7) probability P_{od}^{VF} detection of ARO for test video images is equal to:

$$P_{od}^{VF}(B_j) = P_{od}^{VF}(B_k) = 1,$$

Where B_j, B_k are test video images of the set $B(\vartheta)_{test}$;

$P_{od}^{VF}(B_j), P_{od}^{VF}(B_k)$ are the value of the probabilities of detecting objects of interest on the test video images, taking into account the qualitative assessments shown in Fig. 7.

In its own, for the studied set of test data $B(\vartheta)_{test}$, the average value of the probability P_{od}^{VF} object detection is:

$$\overline{P_{od}^{VF}(B(\vartheta)_{test})} = 0{,}89 ,$$

Where $\overline{P_{od}^{VF}(B(\vartheta)_{test})}$ is average probability P_{od}^{VF} value detection of objects in the test set $B(\vartheta)_{test}$ video images B_j.

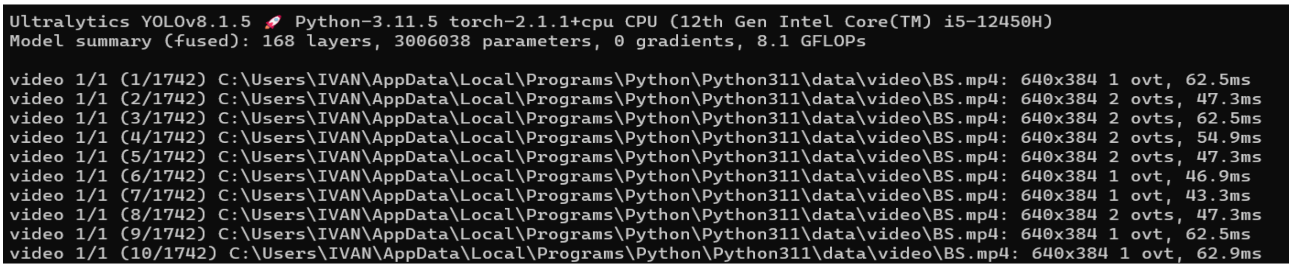
This means that the satisfactory requirements of the air reconnaissance system for ensuring the required level of reliability are fulfilled [30]:

$$P_{od}^{VF} \in [0{,}8 , 0{,}9].$$

In turn, the evaluation of the operational efficiency of the processing of test data of aerial reconnaissance is shown in Fig. 8. In the course of experimental studies, a personal laptop with the following characteristics was used to evaluate efficiency:

- processor - 12th Gen Intel(R) Core(TM) i5-12450H 2.00 GHz;
- RAM - 16.0 GB;
- system type - 64-bit operating system, x64 processor.

It should be noted that the laptop was chosen as a computer for the purpose of simulating data processing at the ground command and control station of UAS.



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Ultralytics YOLOv8.1.5 🚀 Python-3.11.5 torch-2.1.1+cpu CPU (12th Gen Intel Core(TM) i5-12450H)
Model summary (fused): 168 layers, 3006038 parameters, 0 gradients, 8.1 GFLOPs

video 1/1 (1/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 62.5ms
video 1/1 (2/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 2 ovts, 47.3ms
video 1/1 (3/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 2 ovts, 62.5ms
video 1/1 (4/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 2 ovts, 54.9ms
video 1/1 (5/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 2 ovts, 47.3ms
video 1/1 (6/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 46.9ms
video 1/1 (7/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 43.3ms
video 1/1 (8/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 2 ovts, 47.3ms
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video 1/1 (10/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 62.9ms
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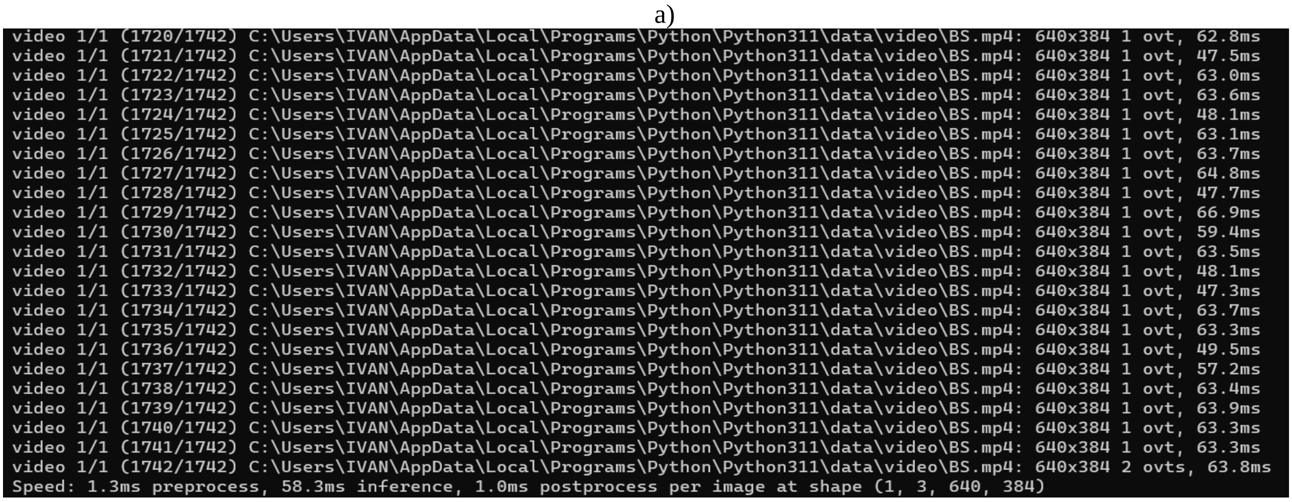
a)



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video 1/1 (1721/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 47.5ms
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video 1/1 (1724/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 48.1ms
video 1/1 (1725/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 63.1ms
video 1/1 (1726/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 63.7ms
video 1/1 (1727/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 64.8ms
video 1/1 (1728/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 47.7ms
video 1/1 (1729/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 66.9ms
video 1/1 (1730/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 59.4ms
video 1/1 (1731/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 63.5ms
video 1/1 (1732/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 48.1ms
video 1/1 (1733/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 47.3ms
video 1/1 (1734/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 63.7ms
video 1/1 (1735/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 63.3ms
video 1/1 (1736/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 49.5ms
video 1/1 (1737/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 57.2ms
video 1/1 (1738/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 63.4ms
video 1/1 (1739/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 63.9ms
video 1/1 (1740/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 63.3ms
video 1/1 (1741/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 1 ovt, 63.3ms
video 1/1 (1742/1742) C:\Users\IVAN\AppData\Local\Programs\Python\Python311\data\video\BS.mp4: 640x384 2 ovts, 63.8ms
Speed: 1.3ms preprocess, 58.3ms inference, 1.0ms postprocess per image at shape (1, 3, 640, 384)
```

b)

Fig. 8. Fragments of the recognition process of ARO on the test data set: a) the beginning of the recognition process; b) the end of the recognition process with the results of evaluating the efficiency of test data processing. Source: developed by the authors

Рис. 8. Фрагменти процесу розпізнавання ARO на тестовому наборі даних: а) початок процесу розпізнавання; б) закінчення процесу розпізнавання з результатами оцінки ефективності обробки тестових даних. Джерело: розроблено авторами

The analysis of the data shown in Fig. 8 shows that the software component of the module allows to ensure the required level of operational efficiency of ARD processing. The average video frame B_j processing time for the test set $B(\vartheta)_{test}$ is:

$$\overline{T_{proc}^{VF}} = 60{,}6 \text{ ms},$$

Where $\overline{T_{proc}^{VF}}$ is average video image B_j processing time using the proposed model for detecting objects of interest.

Next, it is proposed to investigate the possibility and toolkit for further integration of the developed algorithm in UAS. At the same time, it is necessary to determine the area of integration - an unmanned aerial vehicle or a command and control station. As for the second direction, the experimental studies are given above (a personal laptop with a developed model of recognition of ARO) and testify to the possibility of using the proposed module in the air reconnaissance system in order to increase the level of operational efficiency of processing and reliability of ARD without using additional computing power.

In turn, the first direction, that is, the implementation of the specified module on board the UAV, involves the transformation (replacement, addition) of the payload of the UAV. For this purpose, it is proposed to use the components of the Raspberry Pi platform, which is quite actively used in the modern world of information technologies for the purpose of practical implementation of computer vision tools [31, 32]. A possible set of auxiliary hardware is shown in Fig. 9 and includes a microcomputer and a video camera.

The technical characteristics of the hardware part of the module under development selected for experimental research are given in Table 1 [31, 32].

Fig. 9. Demonstration of a set of hardware components for integration on board UAV of tactical class. Source: developed by the authors

Рис. 9. Демонстрація набору апаратних компонентів для інтеграції на борт БПЛА тактичного класу. Джерело: розроблено авторами

Table 1 - Technical parameters of SHM components based on the Raspberry platform

No.	A hardware component	Specifications
1	Microcomputer	Raspberry Pi 4 Model B 8GB
	Processor	Broadcom BCM2711, Quad core Cortex-A72 (ARM v8) 64-bit SoC @ 1.5GHz
	RAM	8GB LPDDR4-2400 SDRAM
	Interfaces	2.4 GHz and 5.0 GHz IEEE 802.11ac wireless, Bluetooth 5.0, BLE; Gigabit Ethernet; 2 x USB 3.0 ports; 2 x USB 2.0 ports
	Video and sound	2 × micro-HDMI ports (up to 4kp60 supported); 2-lane MIPI DSI display port; 2-lane MIPI CSI camera port; 4-pole stereo audio and composite video port
	Multimedia support	H.265 (4kp60 decode); H264 (1080p60 decode, 1080p30 encode); OpenGL ES 3.0 graphics
	Supply voltage	5V DC via USB-C connector (minimum 3A); 5V DC via GPIO header (minimum 3A); Power over Ethernet (PoE) enabled (requires separate PoE HAT)
2	Camera Raspberry Pi Camera Module 3 Wide	Sensor: Sony IMX708 Resolution: 11.9 megapixels Sensor size: sensor diagonal 7.4 mm Pixel size: 1.4 µm × 1.4 µm Horizontal/vertical: 4608 × 2592 pixels Common video modes: 1080p50, 720p100, 480p120 Output: RAW10 Format Autofocus system: autofocus with phase detection Ribbon cable length: 200 mm Cable connector: 15 × 1mm FPC Operating temperature: from 0°C to 50°C

The analysis of the data given in Table 1 shows that the proposed components for the formation of SHMs have quite high computing resources in conditions of compact dimensions and low energy requirements, which allows creating conditions for their further integration into the composition of the payload of tactical-level UAV.

Experimental studies of the effectiveness of the studied module in conditions of autonomous use from the standpoint of ensuring the necessary level of data processing indicate that time delays for video image processing are increasing. The average time of processing a video frame of the test set $B(\vartheta)_{test}$ under the conditions of use of the specified hardware component is:

$$\overline{T_{proc}^{VF}} = 325{,}1 \text{ ms.}$$

This is due to a decrease in computing power compared to the CCS modeled above (notebook specifications). However, the advantage of using the specified module is to ensure the required level of reliability, since the same recognition model is used.

Thus, it can be concluded that the use of the proposed variants of software and hardware modules for the automated detection and recognition of ARO for unmanned aircraft systems (CCS, UAV) allows to create conditions for increasing the level of operational efficiency of video image processing and the reliability of aerial reconnaissance data.

5. Conclusions

In order to solve the problem of increasing the level of video image processing efficiency and data reliability in the air reconnaissance system under the conditions of UAS use, a SHM of automated detection and recognition of ARO is proposed. The results of experimental studies of the integration possibilities of the specified module in UAS indicate that:

1. The integration of the developed module at command and control stations allows to ensure the necessary level of operational efficiency of video image processing and reliability of air reconnaissance data, namely:

- average processing time $\overline{T_{proc}^{VF}}$ video images with the use of the developed model of detection of ARO is 60,6 ms;

- average probability value P_{od}^{VF} detection of ARO meets the requirements of the aerial reconnaissance system: $\overline{P_{od}^{VF}(B(\vartheta)_{test})} = 0{,}89$.

2. In turn, the integration of the developed module on a tactical class UAV allows you to ensure the required level of reliability of air reconnaissance data, but at the same time the time delays for data processing increase, i.e. $\overline{T_{proc}^{VF}} = 325{,}1$ ms. This is due to a decrease in computing power used for data processing.

Further scientific research will be aimed at improving the proposed software-hardware module in the direction of reducing the algorithmic complexity of the software component, increasing the accuracy of detecting objects of interest in accordance with the requirements of the aerial reconnaissance system, and further practical implementation for various classes of unmanned aircraft systems in order to increase the level of processing efficiency and reliability of air reconnaissance data.

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Отримана в редакції 12.03.2024. Прийнята до друку 18.03.2024. Received 12 Mach 2024. Approved 18 Mach 2024. Availablein Internet 10 April 2024