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[1]V. M. Sineglazov,
[2]A. O. Shvidchenko

# ARTIFICIAL INELIGENCE FOR SYNTHETIC APERTURE RADAR IMAGE PROCESSING

[1,2]Faculty of Air Navigation, Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine
E-mails: [1]svm@nau.edu.ua ORCID 0000-0002-3297-9060,
[2]andrey.shvidchenko@gmail.com

***Abstract*****—***The object of this research is the processing of synthetic aperture radar (SAR) images using artificial intelligence. The subject of the study focuses on the utilization of artificial intelligence for the object detection on SAR images. The primary goal of this thesis is to investigate the principles of SAR operation, analyze various systems for detecting anomalous objects in soil, develop an intelligent system for processing SAR images, and evaluate the potential of the developed system for the classification of explosive objects. The research methods include the analysis of existing literature and programming in Python. The findings and materials from this thesis are recommended for use in the analysis of current underground anomaly detection systems, the potential application of artificial intelligence and machine learning in demining processes, and the examination of radar image processing methods.*

**Index Terms—**Artificial intelligence; intelligent processing; intelligent system; machine learning; neural networks; synthetic aperture radar; unmanned aerial vehicle.

## I. INTRODUCTION

Nowadays, the topic of demining large areas has become of great importance. As of March 2, 2023, the area of mined territories in Ukraine is about 180,000 square kilometers, approximately 40% of the entire territory of Ukraine. At the same time, demining is a very complex process. This is evident in the example of Belgium, where the demining of battlefields from World War I is still ongoing. Demining is a procedure that includes the complete neutralization and removal of mines, booby traps, unexploded improvised explosive devices, and explosive materials from a designated area. The main goal of this process is to ensure the safety of the local population.

Humanitarian demining, while an extremely important component of post-conflict or post-war recovery, can still face a number of challenges, especially when using metal detectors. These problems can arise for various reasons, from technical limitations to difficulties working in areas with a significant amount of metal objects.

Typically, demining is carried out by a team of sappers with metal detectors. This method, while effective, is also dangerous for the sapper. Ground and aerial drones offer the possibility of making the mine detection process safe for the people conducting demining operations.

First of all, the technical limitations of metal detectors can pose serious obstacles to effective humanitarian demining. For example, some metal detectors may be insensitive to small or masked metal objects, making them less effective in detecting small explosive objects. In addition, the limited penetration depth of metal detector signals can make it difficult to detect buried mines or other objects at significant depths.

Secondly, there is the possibility of false positive and false negative signals from metal detectors. False positive signals can result from detecting metal objects that are not explosive, leading to wasted time and resources on checking and disposing of harmless items. On the other hand, false negative signals can result in missing potentially dangerous objects, endangering the safety of sappers and residents of the restored areas.

The third problem concerns the difficulties of working in areas with a high concentration of metal objects. For example, in places with building debris or during the clearing of land from military objects, there may be a significant concentration of metal objects, complicating the accurate detection of explosive objects among other metal debris.

To overcome this problems, we can use UV`s with Synthetic Aperture Radar (SAR). However, this raises the issue of navigation and positioning of such drones, followed by the processing of received images and the automatic creation of a geographic information map of the area with the coordinates of the mines and their burial depth. The best current method is the processing of SAR images using artificial intelligence.

## II. CLASSIFICATION OF EXPLOSIVE OBJECTS

The classification of explosive devices is necessary for accurately identifying the type of ammunition, mine, etc., and for determining the method of neutralization by sappers. In our case, for the development of an intelligent system for processing synthetic aperture radar (SAR) images, it is necessary to know the sizes of mines and the depths at which they are buried.

An explosive device is an object that contains explosive substances and can lead to an explosion, injury, or damage due to careless handling. Such items may include explosive devices, ammunition, mines, grenades, bombs, explosive substances, or any other materials that have the potential to explode. They can be hazardous to the life and health of people and can also cause damage to property and infrastructure.

Explosive devices generally include.

- *Explosive substances:* chemical compounds or mixtures capable of rapid chemical transformation under certain external influences (heating, impact, friction, explosion of another explosive device) that propagate themselves, releasing a large amount of energy and forming gases [1].
- *Ammunition:* armed or explosive materials intended for use in combat. These can include shells, shell parts, explosive devices, firearm ammunition, rockets, mines, and other similar means designed for use in warfare or military training. They can vary in types and calibers depending on the purpose and type of weapon for which they are intended.

### *A. Introduction to SAR*

A Synthetic aperture radar (SAR) is a radar system that uses radio waves to create high-quality images of the Earth's surface. The main idea is to simulate a large antenna aperture by combining signals received from a moving antenna during its motion.

Typically, the width of the radio waves used by this type of radar ranges from several meters to a few centimeters, which is much larger than the wavelength of visible light used for ordinary optical images. The wavelengths of SAR fall within the microwave part of the spectrum.

Synthetic aperture radar images appear almost photographic, but they are not photographs; they are two-dimensional holograms. Unlike satellite images, the radar does not measure the target scene from above; it measures it from the side at a considerable distance. The resulting image represents a bird's-eye view with many shadows, where each pixel directly reflects the flight trajectory of the aircraft/satellite in range and azimuth coordinates.

The radar works by emitting radio signals and then receiving the returning echoes of the pulses, thus forming an image of the object that reflects the signals. It is known that the larger the antenna aperture, the higher the resolution of the obtained image. Therefore, to get a high-quality image, it is necessary to increase the physical aperture, i.e., use a large-sized antenna. Each pulse has unique characteristics [2].

The most important property of radar for imaging is that its relatively long waves penetrate through layers, dust, and even volcanic ash, and it can obtain images regardless of most weather conditions. Considering that Earth is an oceanic planet, with a significant amount of water vapor constantly condensing into clouds over large areas of its surface, radar is the primary remote sensing technology and becomes the main source of images when cloud cover interferes with other means of data acquisition.

The main parts of the SAR system are depicted in Fig. 1. The pulse formation block generates pulses with a bandwidth corresponding to the desired range resolution. These will be amplified by the transmitter and transmitted to the antenna through the circulator. The receiver takes the output signal of the antenna (scene echo), amplifies them to an appropriate level, and applies a band-pass filter. After demodulation and A/D conversion of the signals, the SAR processor starts computing the SAR image. Additional motion information will be provided by the motion measurement system. The radar control unit organizes the sequence of operations, including the timing schedule [3].

The key components of a SAR system can be highlighted as follows:

- Antenna is the most crucial part of the radar is the antenna, responsible for emitting radio signals and receiving echo signals from the Earth's surface. In a SAR system, the antenna can be mobile to provide the necessary aperture.
- Transmitter and receiver are responsible for generating radio signals, transmitting them through the antenna, and receiving the reflected signals.

Platform with mobility. To create images of the Earth's surface, the antenna must be mobile relative to the object. This can be achieved using a mobile platform (aircraft, satellite) on which the radar is mounted.

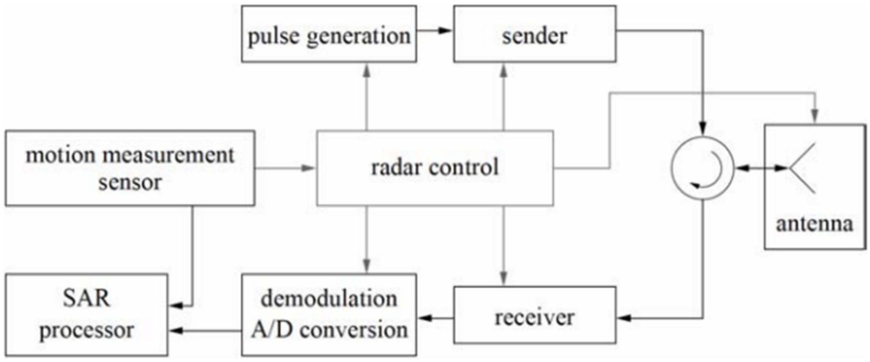


Fig. 1. Structural Diagram of a Synthetic Aperture Radar

*B. SAR Parameters*

*Geometry of Radar Data Acquisition*. Radars can collect data at various angles relative to the flight direction. Generally, data is collected at a right angle to the flight direction. However, some radars can adjust the data collection angle to cover areas in front of or behind the primary direction.

The angle at which the radar is directed downward from the horizon is called the incidence angle. This angle is defined as the difference between the vertical vector at the observation point and the line connecting this point to the antenna. The grazing angle is the complement of the incidence angle. For example, an incidence angle of 55° corresponds to a grazing angle of 35°, and vice versa.

The data collection process by the radar is illustrated in Fig. 2. During this process, the radar emits signals at a wide angle and collects data from numerous individual pulses. This allows for the creation of radar images with information on range and azimuth. Range refers to the size along the wide angle, and azimuth refers to the direction orthogonal to this angle.

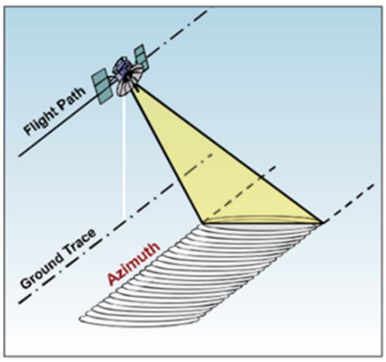


Fig. 2. Radar Data Collection Process

*Wavelength*. Radio waves are part of the electromagnetic spectrum with wavelengths significantly longer than those in the visible light range, typically in the range of tens of centimeters. Penetration is a key factor in the choice of wavelength: the longer the wavelength (shorter frequency), the greater the penetration through vegetation and soil. Table I shows the wavelengths used by SAR systems.

*Principle of the Stripmap Method*. In the Stripmap mode, the antenna remains fixed in a certain direction. The antenna beam scans the Earth's surface at a constant speed, creating a continuous image of the area. The process of transmitting and receiving signals occurs parallel to the movement of the platform, allowing for high-quality, high-resolution images. After receiving the signal, processing algorithms, such as inverse filtering, are used to form the final image.

TABLE I. TYPICAL WAVELENGTHS USED IN SAR SYSTEMS

| **Frequency Band** | **Wavelength Range** |
|---|---|
| P-band | 30 – 100 cm |
| L-band | 15 – 30 cm |
| S-band | 7.5 – 15 cm |
| C-band | 3.75 – 7.5 cm |
| X-band | 2.5 – 3.75 cm |
| Ku-band | 1.67 – 2.5 cm |
| K-band | 1.11 – 1.67 cm |
| Ka-band | 0.75 – 1.11 cm |

## III. OVERVIEW OF MODERN MINE DETECTION SOLUTIONS USING SAR

Robotic mine detection systems, although effective, are still not widely spread. Currently, such systems are difficult to classify as they are mainly created by enthusiasts from various countries in small quantities and differ in both their principle of operation and method of application.

Synthetic Aperture Radars are becoming increasingly accessible to a wide range of researchers, thereby expanding the capabilities and applications of these radars. The goal of this section is to familiarize the reader with the existing systems for the detection and localization of explosive devices based on SAR.

*A. Findmine Ground Penetrating Synthetic Aperture Radar (FM-GPSAR)*

"FM-GPSAR" is a system based on UAVs (Fig. 3) for detecting and localizing shallowly buried objects such as mines and unexploded ordnance. GPSAR allows for the detection of objects beneath the Earth's surface or hidden in dense vegetation. However, penetration depth is significantly reduced in wet conditions. With the GPSAR system, it is unnecessary for the system operator to directly expose themselves to significant risk. The main issues with the system include localization accuracy, radar dynamic range, sensor synchronization, and computationally intensive data processing, similar to tomography. Suspect locations identified by GPSAR can be further classified using our drone carrying a metal detector [4]. The complex was developed by the non-commercial company "Findmine," based in Illertissen, Bavaria. "Findmine" is engaged in UAV-based developments in the field of safe demining.

Fig. 3. FM-GPSAR System

According to the manufacturer's website [4], the technical characteristics and features of the system are as follows:

- UAV with Ground Penetrating Radar (GPR) in the frequency range of 1 GHz – 4 GHz: This allows the system to detect objects buried at shallow depths.
- Range resolution on the ground determined by the radar's bandwidth: The ability to distinguish between objects at different distances from the radar.
- Cross-range resolution determined by the synthetic aperture: The ability to distinguish between objects that are side by side.
- Depth resolution through soil modeling based on Digital Terrain Model (DTM) and multiple perspectives: Allows for accurate determination of the depth at which objects are buried.
- Deep images up to -20 cm obtained after intensive offline processing: The system can create detailed images of the subsurface up to a depth of 20 cm.
- Algorithms require precise (+ / –1 cm) reconstruction of the flight trajectory: High precision in the UAV's flight path is crucial for accurate data processing.
- Search flight speed of 2700 m²/hour: The area covered by the UAV per hour of flight.
- Processing time of 3–30 hours per hour of search flight: The time required to process the data collected during the flight, depending on the complexity and resolution of the data.
- Processing depends on voxel resolution and observation distance: The granularity of the data and the distance from which observations are made.
- Typical voxel resolution of 1 cm – 5 cm: The standard resolution of the 3D pixels (voxels) in the subsurface images.

These features highlight the capabilities and challenges of using UAV-based SAR systems for mine detection, emphasizing the need for high precision and substantial data processing (Fig. 4).

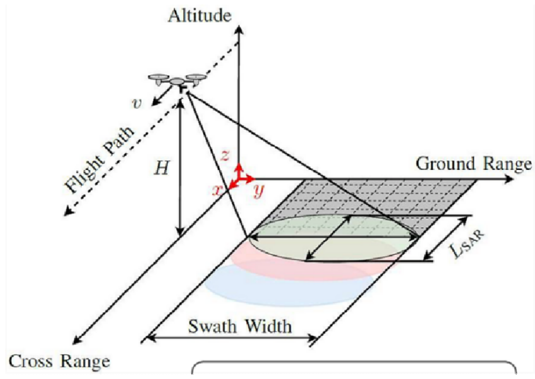


Fig. 4. Geometry of FM-GPSAR Data Acquisition

*B. Forward Looking Ground Penetrating SAR (FLGPSAR)*

FLGPSAR is a system based on a turf vehicle (Fig. 5) capable of detecting both metallic and plastic mines along the vehicle's path. This is made possible by a forward-looking broadband GPSAR, which operates in the frequency range of 400 MHz to 4 GHz [5].

The data collected by the system is processed using various target-sensor geometries. As the platform moves, the system generates 2D or 3D images, coherently combining them using a method called Multi-look processing. This method reduces noise and produces clearer images, a technique also employed by the system described in the following section.

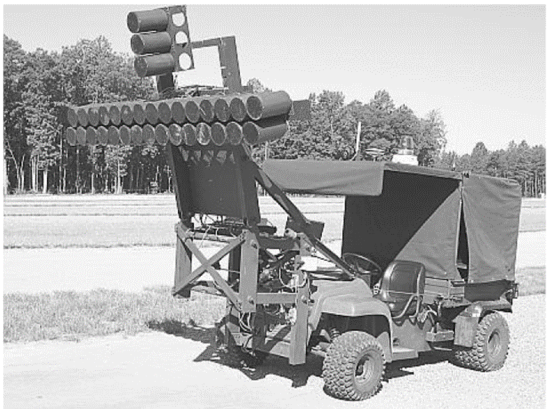

Fig. 5. FLGPSAR System on a Turf Vehicle

The system was tested on both metallic and plastic mines buried at different depths. There were no issues with detecting metallic mines; for testing purposes, an anti-tank mine TM62 buried at a depth of 5 cm was used. The resulting images covered an area of 4.5 m by 5 m at a distance of 4 m from the vehicle. However, detecting plastic mines proved to be more challenging due to their low dielectric contact with the ground.

The main advantage of this system is its ability to detect directional mines, such as MON-100 and others. These mines are typically placed near roads or paths, hidden under dense vegetation, and pose a serious threat to vehicles and personnel. Mine activation can occur through command or tripwire. To assess the effectiveness of the FLGPSAR system against directional mines, a dummy mine was created. At the PSI engineering facility in Long Beach, Mississippi, a situation was modeled where a metal plate, approximately the same size as the MON-100, was attached to a tree 10 meters from the FLGPSAR trajectory and 1 meter from dense vegetation. This plate was not visually detectable. However, the system performed excellently and successfully detected the improvised mine without any issues.

FLGPSAR's Key Features and Capabilities:

- Operates between 400 MHz and 4 GHz, allowing for the detection of both metallic and non-metallic mines.
- Utilizes Multi-look processing to generate 2D and 3D images, enhancing image clarity by reducing noise.
- Capable of detecting mines directly in the vehicle's path, ensuring safe passage.

FLGPSAR's ability to detect various types of mines and its advanced image processing techniques make it a valuable tool in demining operations, offering a safer and more efficient method of mine detection compared to traditional techniques.

*C. System for Detecting Tripwire Mines Using Synthetic Aperture Radar*

A mine detection system designed by students Markus Schartel, Ralph Buer, and their supervisors, Winfried Mayer and Christian Waldschmidt, from the Institute of Microwave Engineering at the University of Ulm, is specifically intended for detecting anti-personnel tripwire mines like the PROM-1. Their design incorporates a UAV equipped with a Synthetic Aperture Radar (SAR) using a bistatic frequency-modulated continuous wave (FMCW) system, operating in the 1 to 4 GHz range. The radar antennas can be manually rotated 360°. The UAV can stay airborne for up to 23 minutes. Data collected by the radar is stored on a single-board computer for further processing after landing [6].

The system was tested for detecting a dummy PROM-1 mine placed in dew-covered grass (Fig. 6). Due to the grass, the stretched tripwires were poorly visible in the initial SAR images (Fig. 7). To enhance the image clarity, multiple images of the scene were taken and combined using a method called Multi-look processing. The improved result can be seen in Fig. 8.

Fig. 6. Dummy PROM-1 Mine Setup in Grass

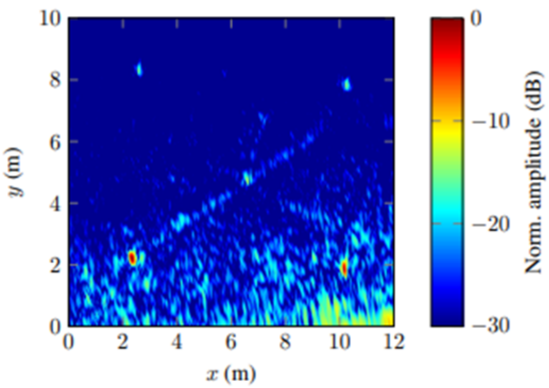


Fig. 7. Initial SAR Image with Poorly Visible Tripwires

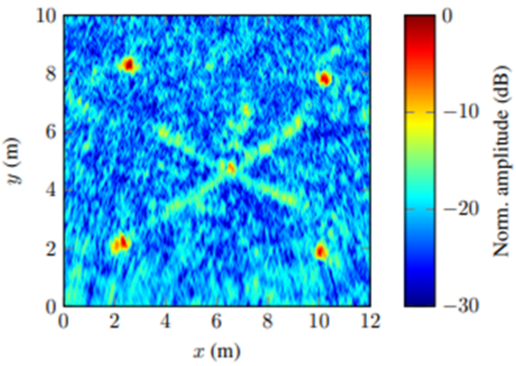


Fig. 8. Enhanced SAR Image Using Multi-look Processing

The system's ability to detect mines and their tripwires, even under challenging conditions like dense vegetation, highlights its potential effectiveness in humanitarian demining efforts. Combining multiple SAR images to improve clarity is a critical advancement in ensuring reliable detection, thereby increasing the safety and efficiency of demining operations.

*D. Application Development for Processing Images Obtained by Synthetic Aperture Radar*

For the efficient use of images obtained by synthetic aperture radar (SAR), it is necessary to find solutions for the rapid and accurate processing of these images. In this context, the meaning of the word "processing" depends on the task at hand. This may involve image classification, segmentation of specific objects in the image, or detection tasks for highlighting and counting objects of a certain type and classifying them.

Modern technologies in the field of image processing using artificial intelligence can help accomplish this task. The use of artificial intelligence significantly reduces the time and resources required for image processing. Although AI is not perfect in terms of accuracy, it can process large volumes of data in a short period and can be retrained for new tasks.

## IV. Choosing a Network for Training

When it comes to processing any image, the choice of neural network (NN) architecture is primarily based on the following criteria:

- speed;
- ease of use;
- detailed documentation describing the model;
- developer support for their product.

You Only Look Once (YOLO) meets all these criteria, providing developers with free access to its products and solutions for various types of image processing tasks. A key feature of this model is the ability to perform tasks in a single pass of the input image through the NN, significantly reducing the time needed to process one image and making it possible to use NN in real-time applications. An additional argument for choosing YOLO is the openness of its architecture and program code.

In the practical part of this work, I decided to use the YOLOv8 model. While it is not the latest model, it is quite accurate and efficient for simple tasks such as segmentation, classification, and detection.

To evaluate this choice, we can compare this model with other YOLO models. Figure 9 shows two graphs, presenting the comparative performance evaluation of different models for image processing based on the COCO average precision (AP) metric, which is used in object recognition tasks. The left graph shows the dependency of COCO AP on latency, and the right graph shows the dependency on the number of model parameters.

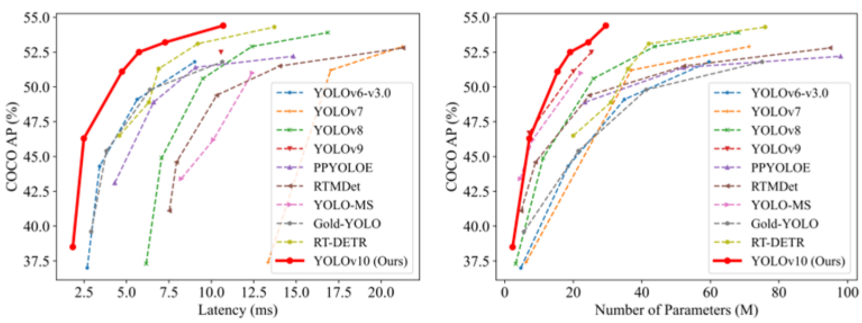


Fig. 9. Comparative Performance Evaluation of YOLO Models

Key Metrics

- *Latency:* The delay before the start of processing.
- *Number of Parameters:* The complexity and size of the model.

Figure Explanations

- *Left Graph*: COCO AP vs. Latency.
- *Right Graph*: COCO AP vs. Number of Parameters.

Despite the fact that the models shown in the graphs lag behind the new YOLOv10 in many parameters, YOLOv8 still demonstrates high performance, especially at low latency values. Under ideal circumstances, it would be preferable to use the latest model in the YOLO series, but the functionality and capabilities of YOLOv8 are sufficient to accomplish the tasks of this work.

The YOLOv8 model offers a good balance between accuracy and processing speed, making it suitable for real-time applications and practical for the tasks at hand.

By choosing YOLOv8, we leverage a well-supported and documented model, ensuring robust and efficient image processing capabilities essential for detecting and classifying objects in SAR images. This choice is also backed by the extensive community and resources available for the YOLO architecture, facilitating easier development and troubleshooting.

## V. Network Training

For network training, the dataset "SARscope: Synthetic Aperture Radar Maritime Images" [7] was chosen. This dataset comprises 640x640 pixel images in ".jpg" format captured by synthetic aperture radar and is used for research in automatic object recognition on the sea surface. The dataset is divided into three sets.

- *Test set*: contains 672 images.
- *Training set*: contains 4717 images.
- *Validation set*: contains 1346 images.

## VI. Program Development

An important aspect of this work is the choice of tools for task execution. Tools refer to the programming language, necessary libraries, and the development environment. The following development tools were chosen.

- *Programming language*: Python.
- *Library*: Ultralytics for integrating the selected YOLO model.
- *Library*: PIL for image processing.
- *Library*: PyQt6 for creating the user interface.
- *Development environment*: PyCharm.

Python was chosen as the programming language. Python is a high-level programming language used for writing various types of programs. It supports several programming paradigms, including object-oriented, procedural, and functional programming, providing developers with flexibility in choosing the approach to solve specific tasks.

The primary argument for choosing Python was the availability of numerous libraries that extend the language's capabilities, allowing it to perform many functions, including machine learning and image processing. Let's look at the libraries used in this work.

Ultralytics is a well-known Python library specializing in implementing computer vision algorithms, particularly for object detection and image segmentation. It gained widespread popularity thanks to its flagship project, YOLO, which is one of the most efficient and fastest algorithms for object detection. Ultralytics supports various model architectures, allowing users to choose the one that best suits their needs, useful for balancing accuracy and execution speed.

One of Ultralytics' main advantages is its simplicity and intuitiveness. The library offers a convenient API that allows quickly integrating computer vision models into various projects. Moreover, detailed documentation and numerous examples help developers quickly grasp the basics and get started.

Python Imaging Library (PIL) is a popular library for working with images in Python. It provides a rich set of tools for image processing and manipulation. Although the original PIL library is no longer supported, its fork named Pillow is a modern alternative that is actively developed and maintained by the community.

PyQt6 is a Python library for creating graphical user interfaces (GUIs) that combines Python with Qt. It provides a wide range of widgets and functionalities for creating cross-platform applications. PyQt6 supports modern standards, including Qt Quick, for developing interactive interfaces. The library easily integrates with other Python frameworks, making it suitable for complex projects.

Additionally, libraries such as os, glob, pylabel, shutil, and yaml were used, but they play a secondary role in the application's work and are mainly auxiliary in preparing the dataset for training.

When choosing a development environment (IDE), the primary requirement was to ensure comfortable programming and debugging of the written program. There are quite a few good IDEs for the Python programming language, but in my opinion, PyCharm is the ideal solution.

PyCharm is an integrated development environment (IDE) for the Python programming language, developed by JetBrains. PyCharm is one of the most popular and powerful tools for Python development, providing many features to enhance developer productivity. PyCharm offers a powerful code editor with syntax highlighting, code completion, refactoring, and navigation. The editor also supports real-time error checking and hints, significantly simplifying coding. It also includes an integrated debugger that allows developers to set breakpoints, execute code step-by-step, analyze variables, and execute expressions on the fly. This makes the code debugging process much more efficient, contributing to writing high-quality, reliable, and error-free code.

## VII. Program Overview

The primary goal of developing this application was to demonstrate the potential for further developments in this field. A distinctive feature of the developed program is its simplicity in both development and use. The core of the application is the YOLOv8 convolutional neural network, which has shown excellent speed and accuracy in object detection tasks. The application's user interface is straightforward, allowing users to easily utilize the trained network for processing either a single image or a group of images.

The "Upload image" button uploads a single image for processing, and after processing, displays the result within the application's window (Fig. 10). The processed image is saved in the project folder.


Fig. 10. Processing single image

The “Upload folder” button allows the user to upload a folder containing images that need to be processed. During processing, a progress bar at the bottom of the application’s window shows the percentage of images processed so far. Additionally, in the user-selected folder, the program creates a separate folder named “processed_images” for the images that have been processed (Fig. 11). The filename of each processed image is saved in the format “processed_image_no_ + original filename.”

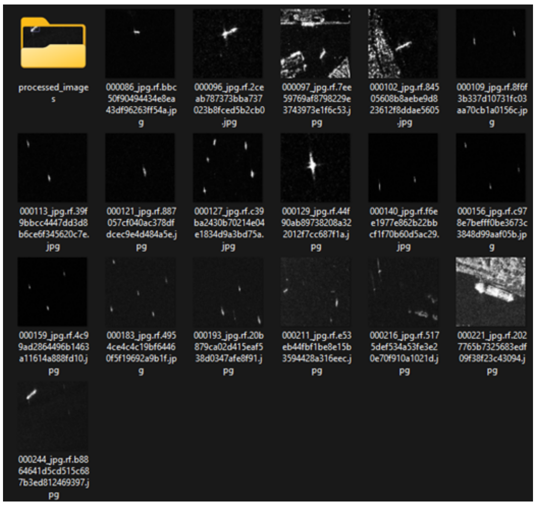

Fig. 11. Processing group of images

The developed program detects maritime vessels in images taken by synthetic aperture radar. Given a dataset for detecting other objects, the model can be retrained accordingly.

## VIII. Prospects

The successful implementation and performance of this application underscore the potential for further developments in the field. Enhancing the capabilities of the YOLOv8 model and refining the user interface could lead to even more powerful and user-friendly tools. Additionally, exploring the integration of newer models such as YOLOv10 could further improve the application's accuracy and efficiency.

## IX. Conclusions

The relevance of SAR (Synthetic Aperture Radar) systems underscores the necessity for developing software solutions for processing radar images, applicable in various fields such as agriculture, ecology, monitoring, and military sectors. Image processing systems significantly streamline tasks that previously required considerable time and resources.

This study analyzed the capabilities of SAR, its parameters, and data collection methods. It described systems utilizing synthetic aperture radar for mine detection. Furthermore, a program was developed that uses a pre-trained neural network on a prepared dataset to analyze radar images and detect maritime vessels. The primary advantage of the developed program is the speed and quality of image analysis. Given a dataset of radar images containing various types of mines, the chosen model can be trained to identify mine types, which is highly valuable for humanitarian demining efforts.

In conclusion, the combination of SAR and the latest advancements in artificial intelligence opens up extensive opportunities. Unfortunately, the implementation of these programs across various fields is hindered by the lack of high-quality datasets for training neural networks. However, I believe that in the future, more such datasets will become available in open access, which will help popularize this research area among developers of all levels.

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**Sineglazov Victor**. ORCID 0000-0002-3297-9060. Doctor of Engineering Science. Professor. Head of the Department Aviation Computer-Integrated Complexes.
Faculty of Air Navigation Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Polytechnic Institute, Kyiv, Ukraine, (1973).
Research area: Air Navigation, Air Traffic Control, Identification of Complex Systems, Wind/Solar power plant, artificial intelligence.
Publications: more than 700 papers.
E-mail: svm@nau.edu.ua

**Shvidchenko Andriy.** Student.
Faculty of Air Navigation, Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine.
Research area: artificial intelligence.
E-mail: sttt912@yahoo.com


**В. М. Синєглазов, А. О. Швидченко. Штучний інтелект для обробки радіолокаційних зображень із синтетичною апертурою**


Об’єктом цього дослідження є обробка зображень радара з синтезованою апертурою (SAR) за допомогою штучного інтелекту. Предметом дослідження є використання штучного інтелекту для виявлення об’єктів на зображеннях SAR. Основна мета цієї роботи – дослідити принципи роботи SAR, проаналізувати різні системи для виявлення аномальних об'єктів у ґрунті, розробити інтелектуальну систему для обробки зображень SAR та оцінити потенціал розробленої системи для класифікації вибухонебезпечних об’єктів. Методи дослідження включають аналіз наявної літератури та програмування на Python. Висновки та матеріали цієї роботи рекомендується використовувати для аналізу сучасних систем виявлення аномалій під землею, потенційного застосування штучного інтелекту та машинного навчання у процесах розмінування, а також для дослідження методів обробки радіолокаційних зображень.


**Ключові слова:** штучний інтелект; інтелектуальна обробка; інтелектуальна система; машинне навчання; нейронні мережі; радар із синтезованою апертурою; безпілотний літальний апарат.


**Синєглазов Віктор Михайлович.** ORCID 0000-0002-3297-9060. Доктор технічних наук. Професор. Завідувач кафедрою авіаційних комп’ютерно-інтегрованих комплексів.
Факультет аеронавігації, електроніки і телекомунікацій, Національний авіаційний університет, Київ, Україна.
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E-mail: svm@nau.edu.ua

**Швидченко Андрій Олександрович.** Студент.
Факультет аеронавігації, електроніки та телекомунікацій, Національний авіаційний університет, Київ, Україна.
Напрям наукової діяльності: штучний інтелект.
E-mail: sttt912@yahoo.com