Automated complex of intelligent monitoring of a solar power plant

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Abstract. A solution for automated monitoring and diagnostics of photovoltaic modules of industrial solar power plants is proposed. The solution is based on the use of an unmanned aerial vehicle with a specialized payload and a ground-based intelligent information and control system to detect problem areas of the station, in particular partial shading and pollution. To perform the detection procedures, a neural network based on the Fast R-CNN architecture with the learning algorithm – Inception v2 (COCO) was used. The results of preliminary tests showed that the accuracy of detecting problem areas is at least 92%. The article presents a mathematical model that allows calculating the installed power monitored by the complex, depending on the type of station and UAV, meteorological parameters, and the performance of computing equipment. Numerical calculations have shown that when using the FIMI X8SE UAV and a computing device based on the RTX2080 GPU, the installed monitored power will be up to 7.5 MW.

1. Introduction
During the operation of industrial solar power plants (SPP), problems often arise related to contamination and damage to the outer surface of photovoltaic modules. The causes of these problems can be divided into external factors (high concentration of dust settling on the surface of the modules, bird droppings) and internal factors (stratification, depressurization and other types of malfunctions caused by natural factors, violation of the assembly process and poor-quality materials) [1,2].

To obtain the required voltage values, the photovoltaic modules are connected in series in thongs. As a result, even partial shading of one module leads to a limitation of the electrical energy generation of the remaining, non-shaded modules connected in series. This phenomenon occurs as a result of a mismatch in voltage at the points of maximum power with other parallel connected strings and leads to a significant decrease in the overall energy efficiency of the SPP [3]. In this regard, there is a need for systematic monitoring of the surface condition of photovoltaic modules, as well as their diagnostics.

2. Existing methods of monitoring and diagnostics of photovoltaic modules
At the moment, there are several ways to solve the problem of monitoring and diagnosing modules. Some of the most common are:

1. A method based on a visual inspection of the surfaces of photovoltaic modules by SPP personnel. This method is one of the first solutions to the problem of monitoring the state of modules, but, at the moment, it is inefficient due to the extreme time cost, exposure to the human
factor and the involvement of additional labor. This solution does not allow for timely response to emerging mechanical damage and contamination of modules, which leads to a decrease in energy efficiency and, as a result, financial losses [4].

2. A method based on the measurement and control of electrical parameters by installing special sensors. Some manufacturers of photovoltaic modules install sensors that control its parameters directly at the manufacturer's factory, but such a procedure leads to a significant increase in cost. In order to reduce the cost of monitoring systems, sensors are installed on some SPP that control the parameters of groups of modules. However, such a solution is still very expensive and forms excessively complex information systems overloaded with sensors [5-7].

3. A method based on the use of unmanned aerial vehicles (UAVs) for photofixing the surface of modules with subsequent manual processing of photo and video materials. This solution is one of the breakthroughs in the field of monitoring the state of photovoltaic modules, due to the increased degree of automation. Its main disadvantage is the need for subsequent manual processing of data received from the UAV, which significantly reduces its efficiency due to the low speed of data processing and the presence of a human factor [8].

Since the described methods have many disadvantages, it is proposed to use an automated complex with a UAV, a system for detecting damage and the degree of contamination of photovoltaic modules based on machine vision and neural network classification methods to solve the problem of monitoring and diagnostics. The use of such systems is the next logical step in the development of automated monitoring systems for objects located on large territories. According to their abilities, these solutions significantly exceed the human capabilities of analyzing and collecting information, maintaining the accuracy of recognition and classification in the course of their work. Based on the above, it becomes possible to formulate the purpose of the study.

The aim of the study is to increase the energy efficiency of industrial solar power plants through the use of an automated complex for monitoring and diagnostics of photovoltaic modules based on the use of unmanned aerial vehicles, machine vision technologies and neural network analysis methods.

3. Using UAVs to solve monitoring and diagnostic tasks
Currently, there are already a number of examples of successful use of UAVs with installed specialized equipment for monitoring and intelligent image analysis, which allows solving problems of recognition and classification of various objects (people, cars, buildings, etc.) [9,10]. However, the solution of these tasks requires high computing power, which imposes certain restrictions on the operation mode of the UAV and negatively affects its capabilities. This is due to the fact that in order to obtain satisfactory results of recognition and classification of objects of interest, it is necessary to obtain images or video images with a fairly high resolution, which leads to a significant decrease in the speed of their analysis. The experience of using such systems shows that the processing of a single image with a resolution of 1920x1080 pixels, when using on-board computing devices, can be performed within a few seconds. As a result, it is necessary to limit the speed of movement of the UAV, which negatively affects the time of its flight. It should also be noted that the presence of a high-performance computing device on board is an additional electrical and weight load of the UAV.

The solution of the problem of monitoring a solar power plant does not require the detection and classification of problem areas in real time. In view of this, it is proposed to perform all resource-intensive calculations on a separate server outside the UAV. This solution will significantly increase the monitoring area and its quality.

4. The principle of operation of the automated complex
To create an automated complex for monitoring and diagnostics of photovoltaic modules, it is necessary to solve multi-level and multi-stage tasks, such as: creating a neural network and an interactive SPP map, configuring and debugging UAVs, developing and configuring a data transmission channel between all the above objects. Figure 1 shows the algorithm for creating an automated complex.
Figure 1. Algorithm for the implementation of an automated complex (creation of a neural network, preliminary preparation for the operation of the complex, neural network analysis).

The first stage of the development of an automated complex is the creation of a neural network, the main task of which is to identify problem areas of the SPP through the use of machine vision technologies and neural network classification. Convolutional deep learning neural networks show the highest accuracy of object recognition in images compared to other types of neural networks [11]. Currently, a fairly large number of algorithms for ultra-precise neural networks have been developed, among which the most promising are: SqueezeNet, ResNet, ImageNet, InceptionV2, InceptionV3, DenseNet, AlexNet and YOLO. In the course of the study, these algorithms were analyzed for the speed and accuracy of operation, as well as the hardware capacities required for this. As a result of the analysis, it was possible to determine that the InceptionV2 algorithm is the most optimal for solving the problem of monitoring a solar power plant for detecting shaded modules, as the most accurate and not resource-intensive among others.

In addition to choosing the optimal algorithm for the convolutional network, a relevant training sample was created, consisting of photos of photovoltaic modules with typical damage, shading and defects (figure 2). In order to convert the sample data into variables that are "understandable" for the neural network, a marking and annotation procedure was performed. The sample markup was implemented for typical deviations of photovoltaic modules from their normal state. To solve this problem, we used the annotation tool (creating labels) – LabelImg.

Figure 2. An example of photos from the training sample.

The next stage in the development of an automated complex is the creation, error checking and training of a neural network on a marked and annotated sample. To exclude the occurrence of retraining of the neural network, during the passage of training epochs, the parameters "loss" and "accuracy" were monitored. In the case of retraining, the neural network will not correctly detect damage, shading and defects of photovoltaic modules, due to a decrease in the ability to generalize data. At the end of the training, a final file is formed with a graph containing all the data necessary for further use.
After creating and training the neural network, an interactive map was built, which is designed to display the results of detection and monitoring of SPP. This will allow the station’s maintenance personnel to quickly respond and eliminate any malfunctions or defects, while practically not spending time searching for problem areas. The interactive map was built on the basis of the station design and the coordinates of the photovoltaic modules.

To ensure the reliable operation of the automated complex, an optimal flight route was drawn up, a take-off platform for UAVs was equipped. The necessary software was installed and configured on the SPP computer. The main functionality of the software is the synchronization of the UAV, the neural network and the interactive map.

Defects are detected by means of data received from the UAV video camera, which are transmitted to the working area of the trained neural network. At the same time, to speed up the work, the storyboard and normalization procedures are pre – performed. The images reduced to the format required for the neural network are processed by machine vision algorithms that detect defects in photovoltaic modules and form a file with the results of their work (figure 3), suitable for further processing. Data with the time stamps of the detection of the shaded module is extracted from the resulting file, which are combined with the time of the video file and data on the geospatial location imported from the UAV logs. Synchronization allows you to determine at which point of the solar power plant the UAV was located at the time of detection of the defect. After that, the processing results are displayed on the interactive SPP map.

![Figure 3. Example of the results of detection of shaded photovoltaic modules.](image)

Thus, the automated complex will increase the energy efficiency of industrial solar power plants through the use of unmanned aerial vehicles, machine vision technologies and neural network analysis methods. The proposed automated complex will be significantly cheaper than the solutions used at large solar power plants based on the use of sensors installed in connecting panels. Also, the implementation of this solution on existing SPP does not require additional costs for their circuit and design reconfiguration. However, with all the advantages, the use of this automated complex is limited by weather conditions (for example, during rain or strong wind), as well as the time of daylight [12].

In order to determine the monitored installed capacity of the SPP (N), a mathematical model was developed that allows evaluating the capabilities of the proposed complex depending on the type of station and UAV, meteorological parameters, and the performance of computing equipment. In addition, the model allows you to calculate the minimum number of complexes required to ensure monitoring and diagnostics of the entire SPP, which is an important aspect of evaluating the economic efficiency of the proposed solution. The value of the monitored power can be calculated from the expression (1).

\[
N = GP_{e}k_{n} \int_{0}^{D} Wdt - 2lGn,
\]

where: \( G \) – the coefficient of the structural features of the SPP and the main characteristics of the photovoltaic modules, (W/m); \( P_{e} \) – the computing power of the equipment; \( k_{n} \) – the coefficient of the frequency of UAV departures; \( D \) – the duration of the shortest daylight day per year, (s); \( W \) – the speed of the UAV taking into account the influence of wind, (m/s); \( l \) – the value of the average distance between the landing platform and the monitored rows of SPP, (m); \( n \) – the frequency of UAV departures.
The coefficient of the structural features of a solar power plant and the main characteristics of photovoltaic modules \((G)\) determines the amount of power generated by the modules that the UAV flies in one second, calculated from the expression (2).

\[
G = \frac{PY}{h},
\]

where: \(P\) – the rated power of the photovoltaic module, \((W)\); \(Y\) – the type of the supporting structure of the modules; \(h\) – the overall size of the module in the direction of movement of the UAV, \((m)\).

The parameter that determines the computing power of the equipment is calculated according to the expression (3). It describes the processing speed of the captured data by the neural network and takes into account the time required to transfer data from the UAV’s memory to the computing device.

\[
P_e = 0.8 \left( \frac{P^N}{P^N_{ref}} \right)^{0.91}
\]

where: \(P^N\) – the performance of computing equipment; \(P^N_{ref}\) – the reference value of performance.

The frequency of UAV departures \((n)\) shows the number of departures required to fly around the territory of the SPP per light day \((D)\), as well as the frequency of battery replacement, the value of which should take into account the climatic conditions in which the complex is operated. Calculated using the formula (4).

\[
n = \frac{D}{d_{uc} k_n} \left(1 - P_e\right)
\]

where: \(d_{uc}\) – the discharge battery UAV under standard test conditions, \((s)\); \(k_n\) – the frequency coefficient of UAV departures, taking into account climatic conditions.

The coefficient of the frequency of departures is determined by the expression (5).

\[
k_n = 1 - ((1.06 \cdot 10^{-2})T - 3.329)^2
\]

where: \(T\) – the ambient temperature, \((K)\).

The speed of the UAV movement under the influence of wind is calculated from the expression (6).

\[
W = 0.5k \left[ \left( V + \frac{C_p \rho S_{UAV} \cos(\epsilon) U^3}{m} \right)^{1/2} \right] + \left( V - \frac{C_p \rho S_{UAV} \cos(\epsilon) U^3}{m} \right)^{1/2}
\]

where: \(k\) is the coefficient that takes into account the aerodynamic features of the UAV; \(V\) – the flight speed of the UAV, \((m/s)\); \(C_p\) – the coefficient of aerodynamic drag of the UAV; \(\rho\) – air density, \((kg/m^3)\); \(S_{UAV}\) – the area of the UAV under the influence of wind, \((m^2)\); \(\epsilon\) – the wind direction relative to the UAV motion vector, \((\text{degrees})\); \(U\) – wind speed, \((m/s)\); \(m\) – the mass of the UAV, \((kg)\).

The flight speed of the UAV is set to ensure optimal detection quality, taking into account the type of the supporting structure of the modules, calculated from the expression (7).

\[
V = 16.2 \exp(-2.5Q)^{0.03}
\]

where: \(Q\) – the set detection quality \((0...1)\).

5. Conclusion

The developed automated complex of monitoring and diagnostics of photovoltaic modules allows solving the problem of operational monitoring of the state of the SPP. A distinctive feature of the use of the complex is the high speed and quality of the examination of the rows of modules. Preliminary tests
have shown that the accuracy of detecting problem areas is at least 92%. In addition, the advantages of the complex include the ease of implementation on industrial SPP. This is due to the fact that its operation does not require additional structural changes in the existing design of the station. Technical and economic calculations of the implementation of this solution at the SPP show that the use of the proposed complex will increase energy efficiency by 2% due to timely diagnostics and prompt provision of information to service personnel.

The mathematical model proposed by the authors allows us to calculate the installed power of the SPP monitored by the complex, depending on various factors. This parameter determines the minimum number of automated complexes required for monitoring the entire station. To assess the effectiveness of the complex, a four-row Crimean SPP "Nikolaevka" (installed capacity – 69.7 MW), with a horizontal arrangement of modules, was considered. Numerical calculations have shown that the use of the complex with the FIMI X8SE UAV and a computing device based on the RTX2080 GPU will allow monitoring up to 6.4 MW of installed capacity. Thus, about 11 complexes will be required to ensure monitoring of this station.

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