

NEXT-GENERATION INFRASTRUCTURE DIAGNOSTICS: UAV-BASED THERMAL IMAGING APPROACHES

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Abstract— Unmanned aerial vehicles (UAVs) are emerging as advanced diagnostic platforms within the power distribution sector, providing a safe, precise, and cost-efficient alternative for infrastructure inspection. By integrating visual imaging, thermal sensing, and LiDAR (Light Detection and Ranging) scanning technologies, UAVs enable the early detection of structural anomalies, quantitative assessment of thermal distribution, and development of detailed spatial documentation of power networks. Such capabilities enhance predictive maintenance strategies, mitigate the probability of critical failures, and contribute to lowering operational expenditures relative to conventional inspection methodologies.

Keywords— UAV, energy industry, critical infrastructure inspections

I. INTRODUCTION

Unmanned aerial vehicles (UAVs), commonly known as drones are increasing in popularity as diagnostic tools in many industries, including power distribution. [1] Rapid advances in aviation technology, sensor miniaturization, and the growing availability of high-end remote imaging devices have enabled the creation of efficient and safe systems for inspecting critical infrastructure such as overhead power lines. Until recently, these tasks were mainly performed using helicopters, which, despite their effectiveness, are expensive to operate, energy-intensive, and subject to high operational risks.

The Robinson R66 helicopter, used by Polskie Sieci Elektroenergetyczne S.A., the company managing the highest voltage power grid (transmission lines above 200 kV) in the Republic of Poland, exemplifies this. That model's average fuel consumption is as high as 87 liters per hour of operation, which, at current JET-A1 fuel prices, translates into an operating cost of over 63 euro per flight hour. Additional financial burdens must also be considered, such as the cost of purchasing the machine itself (0,9-1,4 million euro), insurance, technical inspections, and the need to hire a pilot licensed to perform highly specialized flights near power infrastructure.

In the context of the above limitations, unmanned aerial vehicles represent a new quality in network diagnostics.

There is a wide range of sensors that can be integrated with UAV platforms, depending on the inspection task. Most commonly used are RGB (red-green-blue) cameras for visual inspection and documentation, thermal imaging cameras (infrared sensors) for detecting overheated components such as connectors or insulators, and LiDAR (Light Detection and Ranging) systems that enable three-dimensional mapping of transmission corridors. Moreover, multispectral or hyperspectral sensors can support the monitoring of vegetation around power lines. The selection of a specific sensor depends on mission requirements, payload weight limitations, and the power and communication capabilities of the unmanned aerial vehicle. Regardless of the type of UAVs enables remote, safe, and cost-effective inspections while maintaining high measurement accuracy. Remaining on the ground, the operator can perform a full assessment of the technical condition of network components – from supporting structures to line accessories, insulator systems, and working and lightning protection cables.

Currently, energy companies are equipped with UAVs that are mostly equipped with only video cameras (e.g., DJI Mini 3 Pro – UAV with maximum take-off mass of 249 g, equipped with gimbaled 4k video camera and battery endurance for 30 minutes). Due to their small size and high-resolution cameras, such drones allow for visual inspections of infrastructure, in particular low and medium voltage. In the absence of thermal imaging cameras, these aerial drones are primarily used for inspecting emergency parts (e.g., broken pole structures, support structures, insulators, or fallen trees) rather than preventing them through planned replacements. Furthermore, due to the closed design of DJI commercial drones, it is not possible to attach any payload. The usage of more complex UAVs nowadays in power distribution inspections is limited due to many factors such as high purchase costs, lack of awareness of the range of applications or attachment to traditional inspection methods. [2, 3, 4, 5]



Figure 1. Low voltage power transmission line – the use of UAVs enabled detailed visual inspection, even at the line-congested spots.

II. RESEARCH METHODOLOGY

During implementation research conducted for the energy industry, the following research methodology was established. In the first phase of testing, performed from 26.05 – 14.06.2025, measurements were taken in limited sunlight (cloud cover above 4 octas), wind speed should not exceed 6 m/s, and measurements were taken at a distance of more than 10 m from energy devices. These conditions were developed based on safety analyses and other work on thermal imaging measurements of energy infrastructure. However, the following parameters were then gradually changed to reflect the actual working conditions of electrical power installers. The final phase of testing (18.07.2025 – 18.08.2025) was conducted under arbitrary conditions related to lighting and the potential for objects to heat up. The only parameters determining the possibility of flight were the drone's operational limitations—maximum wind speed below 12 m/s and no atmospheric precipitation. [6, 7, 8, 9, 10, 11]

The work was carried out in multiple ways on transmission infrastructure and photovoltaic farms. In the case of power lines, cooperation was established with one of the Polish energy companies, on the basis of which experts identified lines with the potential for deviations in the thermal imaging picture. Due to the terms of cooperation, it is impossible to indicate the exact location of overhead lines, due to that fact the location of research is unpublic. In the case of photovoltaic farms, they were selected at random, and the flights were carried out on the basis of consents obtained from infrastructure managers in Jaworzno and Bytom in the Silesian-Zagłębie agglomeration.

The flights over the photovoltaic (PV) installations were carried out in accordance with the IEC (International Electrotechnical Commission) standard, both in terms of technical issues such as the type of camera, meteorological conditions such as cloud cover and wind, and operational aspects such as maximum flight speed. In order to ensure maximum accuracy of the thermal image for PV farm inspections, an analysis of obstacles in the take-off field was performed each time and the flight altitude was adjusted. In the case of large farms, a thermal imaging map was created for analysis. The maximum GSD (Ground Sample Distance) was set at 3 cm/px, which complies with surveying standards.

Importantly, during the flights, meteorological parameters such as wind speed and direction, ambient temperature and relative humidity were monitored using a handheld multimeter.

All of the flights were performed using a DJI Matrice 4T drone equipped with wide-angle, telephoto, and thermal imaging cameras with an image resolution of 640x512 pixels and a radiation reading range of 8 to 14 micrometers. The temperature measurement accuracy is ± 2 degrees Celsius or $\pm 2\%$, whichever is higher, with a measurement range from -20 to +150 degrees Celsius. The camera is equipped with a 28x digital zoom. The maximum take-off weight of the drone is 1420g, which allowed it to fly in the OPEN A2 license category. In practice, this resulted in easy access for power emergency repair crews.

A detailed analysis of the thermal image was performed using the DJI Thermal Analysis Tool 3 software, in particular using the following functions: average temperature of a polygon and a section – this function also indicates the minimum and maximum temperatures. In addition, individual measurement points were added at particularly hot spots.

III. VISUAL INSPECTION

RGB cameras mounted on unmanned aerial vehicles enable visual inspection of infrastructure both in real time and based on recorded images available after the device has landed. Using these images, employees of power transmission companies can assess the condition of poles and their protective coatings against corrosion. In addition, they can check the quality of workmanship and joint assembly, as well as visually assess the condition of key components such as insulators, brackets, vibration dampers, and surge arresters.



Figure 2. Detailed view of isolators - with usage of hybrid zoom it is possible to accurately inspect the technical condition of the implemented devices.

The usage of unmanned aerial vehicles enables inspection of devices that are difficult to reach by a pedestrian assembler or typical power company vehicles, for instance 20 m mobile platform. UAVs equipped with IR (InfraRed) lenses can be used not only for routine inspections, intended to lead to the detection of any irregularities and their subsequent rectification, but also during afflictive malfunctions, especially during stormy weather conditions. The theoretical range of drones usually exceeds 5 km (taking the DJI Matrice 4T as an example, the range declared by the manufacturer is 7 km). However, the real available distance of UAV from

remote controller (RC) it is limited by any obstacle that causes distortion of the radio wave (no matter whether drone uses 2.4 or 5.8 GHz connection frequency). Moreover, the flight range is limited by the law (according to Regulation (EU) 2019/947), in beyond visual line of sight flights – BVLOS, the maximum distance between pilot and drone, without an airspace observer is 1 km, with an observer it is just 2 km. All in all, with maximum extended distance of 4 km (having 3 crew members) it allows, under real conditions, for electricians to fly close enough to critical area, scan its surroundings and visually evaluate damages and plan emergency restoration. [6, 13]



Figure 3. The attachment of the isolator system bracket with an apparent anomaly (unscrewed nut of the attachment clamp). The photo was taken from 8 m using a camera with 16x optical zoom and 200x hybrid zoom.

IV. THERMAL IMAGING INSPECTION - PRINCIPLES OF OPERATION AND DIAGNOSTIC SIGNIFICANCE

The thermal imaging cameras are being used in power transmission inspection since its civil development in 1990s, since that time it became one of the key tools used in diagnostics. Infra-Red camera is an optoelectronic sensor, that logs infrared radiation from all bodies of temperature higher than 0K – absolute zero. The thermal energy emitted by objects is received by a transducer and then converted into an electrical signal, which is converted into an image visible to the operator in the form of a so-called thermogram. [8, 10]

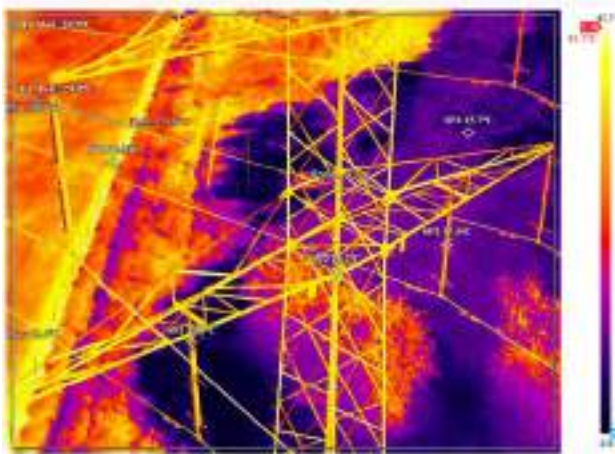


Figure 4. Thermal imaging photo of 220 kV HV power line transmission line pole, measuring points on key elements (lightning conductor, working conductors, pole structure, insulators and surroundings) are marked.

The phenomenon is based on the principle of black body radiation. The basic relationship of this phenomenon is based on the directly adjacent amount of radiated heat in the infrared range, which varies depending on the temperature. What a thermal imaging camera does is not measure temperature directly, but rather the intensity of radiation, which correlates with surface temperature. Such images – usually presented in the form of a color gradient (depending on the settings, usually IronRed, showing the hottest areas in white and red and the coldest in dark blue and blacks) – show the temperature distribution in the object under examination. Thermovision technology is invaluable in the context of power grids. It allows for the detection of so-called hot spots, i.e., places where infrastructure components overheat. The most common causes of this phenomenon are material defects, mechanical damage, degradation of insulating coatings, or poor-quality electrical connections. Effectively, this means increased electrical resistance at a given point, which, according to Joule's law ($Q = R \cdot I^2 \cdot t$; Q – heat emitted, R – electrical resistance, I – electrical current, t – time), results in increased heat emission. A conductor with increased resistance heats up more than other components, which can be easily identified on a thermal image. [12] Defects and abnormalities of this type frequently remain undetected by conventional optical inspections as they do not appear as physical damage. Meanwhile, local overheating can lead to progressive degradation of the component and, in extreme cases, to short circuits, insulation damage, fires, or emergency blackouts of entire sections of the grid. Detecting temperature anomalies in advance allows them to be quickly remedied before they become a hazard to the continuity of electricity supply. [2, 13]

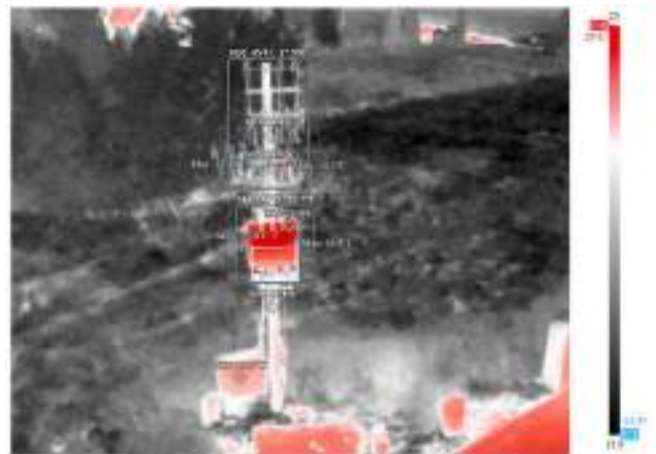


Figure 5. Low-voltage overhead transformer substation in Modlnica, near Cracow, Poland – there is a visible heat radiation from transformer itself and some hotspots (with temperature about 19,2°C) at the insulator section above.

V. 3D INSPECTION – LIDAR

The application of LiDAR (Light Detection and Ranging) technology offers the ability to perform 3D scanning of a given section of the transmission network, poles, and elements on poles, like the insulator system, using a laser beam. Likewise, the LiDAR system emits short pulses of light, usually in the infrared range, which, upon encountering an obstacle—such as the ground, technical infrastructure

components, or plants-are reflected and recorded by a receiving detector. The time of flight of the pulse is measured with high accuracy and forms the basis for calculating the distance between the sensor and the reflection point.

As a result of this process, a so-called point cloud is created, i.e., a spatially distributed set of data describing the geometry of the environment. For each point, information is recorded not only about its XYZ coordinates, but also about the intensity of the reflection, and in advanced systems, also about the number of reflections from a single pulse, which allows for the differentiation of vegetation layers or complex structures.

Considering power applications, LiDAR enables precise mapping of overhead lines, pole locations, and the position of wires relative to the ground and nearby objects. This allows for assessing infrastructure compliance with regulatory requirements for phase separation and minimum safe distances. Furthermore, scanning the same areas regularly allows for the analysis of changes over time, the identification of potential collisions with vegetation, and the planning of preventive measures. A high spatial resolution and the ability to operate in difficult lighting conditions make LiDAR technology a particularly useful tool for monitoring critical infrastructure.

VI. ADVANTAGES OF USING UAV IN TERMS OF SAFETY AND ECONOMICS

Traditional methods of power transmission line inspections characterized by high operational risk. Considering the necessity of physically climbing overhead line poles, there is a potential hazard of falling or electrocution for employees of energy distribution companies. Helicopter inspections, on the other hand, while less direct, still carry a high risk of collisions, high costs and a not inconsiderable environmental impact (exhaust emissions, noise, fossil fuel consumption). The application of UAVs unites the most advantages in terms of both economy and safety.

The unmanned aerial vehicles obviate the necessity for human attendance in hazardous areas, allowing for precise control from the ground. Their advanced maneuverability and ability to hover near grid components enable close-range photography (even 5–10 m) using multi-view optical and digital zoom. Furthermore, flight data can be analyzed instantaneously, and if necessary, a second flight can be scheduled on the same day.

Economics of this solution are equally attractive. Cost of purchasing a modern unmanned aerial vehicle range from €7,000 to €9,500, while cost of training operators and obtaining required permits (STS) ranges from €235 to €1,400. In contrast to helicopters, drones do not require expensive fuel or servicing by certified aircraft mechanics. The operating costs are reduced to charging batteries, seasonal maintenance, propeller replacement, or sensor cleaning.

VII. PHOTOVOLTAIC POWER STATION'S INSPECTION

The use of drones equipped with thermal imaging cameras allows for quick and precise inspections of photovoltaic farms. According to the IEC TS 62446-3 standard, such inspections must be performed every 4 years at each photovoltaic farm. However, regular inspections allow for faster detection of failures, resulting in lower economic losses and a lower risk of dangerous situations such as fire. [14]

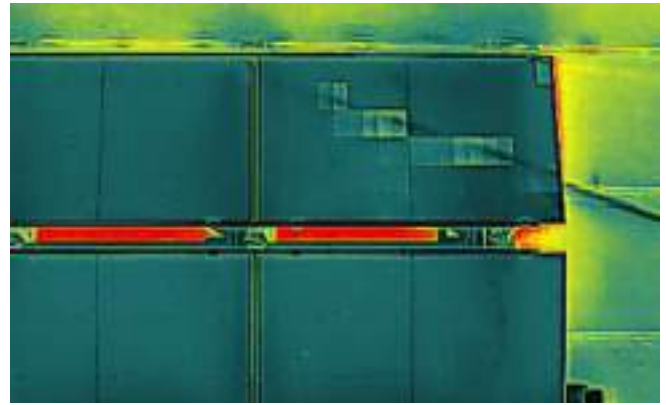


Figure 6. Photovoltaic (PV) panel with visible thermal distortions – deflection of PV modules.

According to proper standard the flyover over PV power plants should be done under specific conditions. First, the weather conditions are strictly regulated, especially the wind speed which can cause false cooling of objects on thermal photos. Secondly, the footage from inspection shall be done in specific way depending on type of check: simplified or extended. [14]

In addition, video cameras allow for visual inspection of panels for dirt and mechanical damage. In combination with a handheld thermal imaging camera and a qualified employee, it is possible to create an inspection report in accordance with the standard, including an examination of the technical condition of PV panels, mountings, and other energy components. [12,15,16]

VIII. CONCLUSION

After completing a series of flights over several designated power lines, slight deviations in thermal radiation emitted from the clamps on the working cables and bridge clamps were observed. A thermal imaging camera was also used to observe localized defects in the corrosion coating and incorrect fastening of the high voltage (HV) line insulator system (i.e. lack of a lock nut).

Implementation recommendations have been developed based on operational parameters tailored to the work of power repair technicians. The most important parameter is the distance between the drone and the power line, due to the desire to minimize risk while maintaining inspection precision. Due to the strong electromagnetic field around the cables, the UAV's remote controller displayed messages about transmission interruptions at distances of less than 5 m (measurements were taken with a laser rangefinder built into the drone's measuring head). This value was therefore set as the limit. Another important parameter is the camera angle, which depends on the height of the transmission line. The greatest deviations were observed when the camera only observed the area below the horizon, due to better radiation measurement reference. In the opinion of the power company's employees, even slight deviations are grounds for further inspection or replacement of the component in a planned rather than emergency mode, without the need to disconnect consumers.

During tests conducted on PV farms, numerous irregularities were detected in the thermal image. In the case of three installations on buildings, numerous hot spots were detected

– points with excessive heat radiation in relation to the surroundings.

It is not possible to directly translate the deviations observed on thermal imaging into a calculation of the energy losses generated by panel damage. However, the layout of hot spots and their area in relation to the entire panel surface may indicate the cause of the failure. For example, if the area of higher radiation covers half of the PV panel, it is most likely that the bypass diode is damaged, which in practice can cause energy losses of 30 to 50%. Individual burnt-out cells can result in losses of up to 5%. In the case of a series-connected installation, however, damage to one panel results in a reduction in the efficiency of the entire installation. For private owners of building installations, the cost of replacing a single panel may be unprofitable due to labor costs, even if the damage causes a 50% loss of the panel's production capacity.

In the case of commercial, large-scale farms, the cost of replacing a panel is much lower due to better access to the installation and the possibility of purchasing panels at wholesale prices. Two out of three of the installations surveyed had numerous deviations in the thermal image on more than 60% of all installed panels. On the basis of observations using a UAV equipped with a thermal imaging camera, reports were prepared in accordance with the IEC standard.

IX. SUMMARY

Unmanned aerial vehicles are fundamentally transforming the monitoring and diagnostics of power transmission infrastructure. The integration of RGB imaging, thermal diagnostics, and LiDAR scanning has enabled highly precise, remote, and economically efficient inspection practices that significantly exceed the possibilities of traditional approaches. UAV-based inspections not only eliminate the risks associated with direct human involvement in hazardous environments but also ensure a high degree of repeatability and standardization of measurements, which is essential in long-term infrastructure management.

A particularly valuable aspect of UAV technology lies in thermal imaging diagnostics. By detecting anomalies in temperature distribution, drones can identify defective or overloaded components at an early stage—often before any visible signs of damage or failure appear. This capability is critical because local overheating can accelerate the degradation of insulators, connectors, and conductors, potentially leading to short circuits or large-scale outages. Early identification and rectification of such problems directly contribute to the security of electricity supply and prevent cascading failures within the grid.

Equally important is the ability to conduct three-dimensional mapping using LiDAR sensors. Point cloud analysis makes it possible to reconstruct the geometry of transmission networks with very high accuracy, ensuring that clearances to vegetation and surrounding infrastructure comply with regulatory standards. Furthermore, by comparing datasets collected over time, operators can monitor the progression of structural wear, environmental impacts, and vegetation encroachment, which in turn supports evidence-based maintenance planning. This capability strengthens predictive maintenance strategies, making it possible to intervene precisely where and when necessary.

The added value of UAV applications extends beyond transmission systems to renewable energy installations. During research flights, numerous defects were identified not only in transmission infrastructure but also in photovoltaic (PV) panels. Thermal imaging revealed irregular heating patterns on the surface of PV modules, indicative of phenomena such as microcracks, soldering defects, delamination, or partial shading caused by environmental factors. These anomalies, often invisible to the naked eye, reduce panel efficiency and, if left unaddressed, may lead to progressive degradation of entire arrays. UAV-based thermography thus provides an effective means of monitoring large solar farms, allowing for the rapid localization of underperforming modules and supporting maintenance teams in optimizing energy yields.

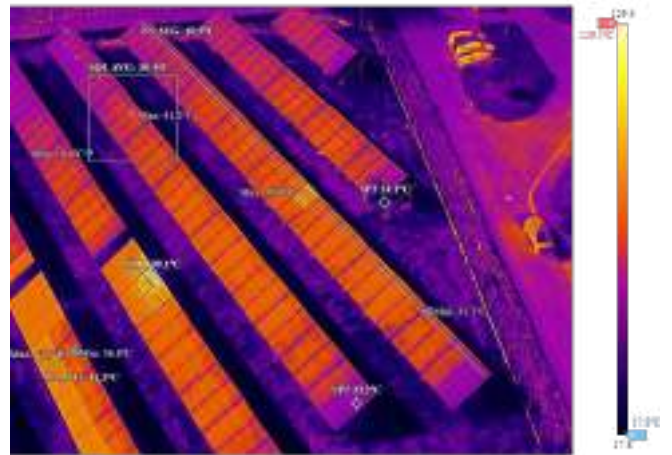


Figure 7. Large-scale photovoltaic farm in a thermal imaging view. Numerous defects are visible, associated with damage to individual cells or entire strings.

Taken together, these results clearly demonstrate that UAVs are not merely supplementary tools but are becoming indispensable in the management of modern power systems. Their capacity to detect a wide spectrum of anomalies—ranging from loose fittings on overhead lines to malfunctioning PV modules—enables a comprehensive approach to energy infrastructure diagnostics. The combination of high spatial resolution, non-invasive operation, and cost efficiency translates into greater reliability of supply, reduction of technical losses, and substantial savings in operational budgets. In the long term, the systematic use of UAV technologies strengthens the resilience of the energy sector, accelerates the integration of renewable sources, and supports the transition toward a more sustainable and digitally managed power grid.

Despite these clear advantages, the widespread adoption of UAV technologies remains constrained by legal and regulatory frameworks. Current aviation laws, such as restrictions on flights beyond visual line of sight (BVLOS), altitude limits, and mandatory pilot certification, restrict the operational range and flexibility of UAV inspections. These regulations, while essential for ensuring airspace safety, limit the full realization of UAV potential in large-scale, long-distance, or densely populated grid environments. Moreover, national and international variations in drone legislation further complicate cross-border implementation, creating challenges for multinational energy operators. [17, 18]

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