Accelerating Power Grid Monitoring with Flying Robots and Artificial Intelligence

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Abstract—**The digital revolution is expected to surpass all previous economic transformations in scale, scope, and complexity. Digital technologies are making electrical grids more connected, more reliable, and sustainable. Several efforts have been made to revamp the electric grid and modernize century-old systems. In the near future, we expect to see a revolution in power grid monitoring with incredible results through artificial intelligence, big data, drones, among others. The business opportunity for using drones in the energy sector is impressive, although very few companies have joined in its implementation. The drone allows the safe remote overflight of high voltage power lines. They can be deployed to detect, inspect, and diagnose the defects of the power line infrastructure. In this paper, we provide a state-of-art of using drones in smart grid monitoring. We demonstrate and propose an architecture based on Faster R-CNN for detecting ice accretion on power lines. Finally, we shed light on opportunities and future trends of these emerging technologies that can guide future research directions.**

***Index Terms*—Smart Grid, Drone, Unmanned Aerial Vehicles Artificial Intelligence, Power Grid Monitoring, Solar Plant.**

I. INTRODUCTION

Drones, "the new flying IoT," or "flying robots," have become essential tools in many areas. Also known by their acronym, UAV (Autonomous Unmanned Vehicles), they can perform an unlimited number of tasks.

Technically, the drone consists of three segments (1) The air segment includes one or more air vectors carrying the payload, such as a camera, (2) The ground segment comprises one or more control and information collection stations, the support team, and (3) the wireless component is a set of data links connecting the ground and air segments [1].

The UAV is an aircraft without a human pilot on board. This autonomy is conferred on these flying robots by the navigation instruments onboard the drone: GPS, inertial station, compass, barometer, etc. Drones can play an active role when they are equipped with a payload to interact with their environment. However, the vast majority of drones play an observer role, and their payload is a sensor such as a simple camera.

Beyond applications leisure and small consumer toys, the primary uses of the unmanned platforms onboard are designated by the acronym "5D" for Dull, Dirty, Dangerous, Dear, Difficult; either repetitive, compromising, dangerous, at a high cost and difficult. Although using a drone allows humans to stay away from danger and take turns throughout the mission, the management of such a platform is a complex task that requires a pilot's presence at all times [2].

The miniaturization of optical sensors, the era of digital imaging, and advances in image processing, driven by the excellent computing power available today, promise the drone mapping sector many perspectives. After being born as flying toys, and after becoming robotic cameras, drones today carry enough intelligence to assist humans in complete autonomy.

Thanks to the versatility and high mobility of UAVs, low-altitude UAVs are extensively used in diverse fields for different applications and purposes. Drones can be used to monitor electrical networks in real-time and broadcast live detailed high-resolution shots of the various production entities, the transmission, transport, and distribution networks. More secure and less expensive than human intervention, drones can replace the inspection procedures traditionally performed by humans [3]. Their use increases mission safety, as inspections of energy assets often require employees and contractors to work at heights. A drone with a thermal image camera can detect overheating parts or places requiring maintenance. This analysis makes it possible to identify, prepare, and secure an intervention on many infrastructure types, such as electricity pylons, wind farms, or photovoltaic panels [4]-[5].

Artificial intelligence (AI) has recently flourished in different applications through advanced machine learning, deep learning, and reinforcement learning. Drones, combined with artificial intelligence, will play a crucial role in various real-time monitoring applications.

All industries can benefit from the technological developments that result, including drones. We show that the classifier based on Faster R-Convolutional neural networks (CNN) gives better results than the more classical methods and can be used for Ice accretion detection on power cables.

This paper defines drones and their addressable marketplace for smart grid monitoring. Two example case studies are provided, UAV-based solar inspections and ice detection on electrical power cables. For the last application, we applied a deep learning architecture, i.e., Faster-RCNN, with ResNet-101 as a backbone network. To the best of our knowledge, Faster-RCNN with ResNet-101 architecture is used for the first time for the ice accretion on electric power lines detection. The images are collected from different online available data sources for testing and training of the model. The real-time image collected from the drone can directly be fed deep learning architecture for ice detection. The framework is capable of assisting Utility companies to remote monitor their installations.

The work presented in the paper is structured as follows. An overview of the drone market is given in Section 2. Section 3 summarized the use of drones in the smart grid. The application of drones for solar plant monitoring is given in Section 4. Section 5 describes the role of the UAV in predictive and application maintenance in the smart grid. The next revolution for the future of drones is given in Section 6. Section 7 provides the conclusion of the work with possible future guidelines.

II. Drones on all fronts

The drone's primary function is to extend human vision beyond the natural horizon to perform at risk or in hostile environments. Drones earned an unsavory reputation. Most people associate them with expensive military aircraft. The military drones were the first to hit the skies, buzzing over combat zones. Recent data shows that practical commercial applications will shape the future of drones.

The non-military drone industry should know a profound change. The usage of drones in business operations has broadened in different sectors. More recently, civilian applications have appeared, such as preventing forest fires, inspecting engineering structures, surveillance of motorway traffic, or collecting meteorological data. Depending on the operational capabilities sought, the drones' size varies on a scale ranging from a few centimeters to several meters. Simultaneously, their weight fluctuates between a few grams for the lightest and up to several tones for the heaviest.

Drone for recreational use and leisure activities should continue to progress. However, a growing number of component suppliers worldwide are experiencing slowdowns or shutdowns in response to the COVID-19, affecting sub-components' availability in a snowball effect [9].

The global commercial drone market size is projected to increase. According to a new market research report titled, *"Unmanned Aerial Vehicle (UAV) Market by Component (Hardware, Software), Class (Mini UAVs, Micro UAVs), End-User (Military, Commercial, Agriculture), type, capacity, and Mode of Operation– Global Forecast to 2027",* the UAV market is expected to grow at a compound annual growth rate (CAGR) of 14.1% from 2020 to 2027 to reach $21.8 billion by 2027 [9].

In terms of volume, the market is expected to grow at a CAGR of 16.2% from 2020 to 2027 to reach 13.2 million units by 2027. In that case, they should be largely overtaken by professional models, estimated to them more than $5 billion. And this strong trend should continue and gain momentum in the coming years, as the professional applications will develop.

A wide variety of types of drones exist, and their characteristics define their fields of application.

Several ambitious reforestation projects are underway around the world. Depending on the objectives sought, different drone systems have been developed, varying in size and capable of carrying a wide variety of sensors. The use of this technology has, therefore, resulted in varying degrees of success.

Recent studies attempt to develop protocols for using drones in several applications such as archeology, search and rescue, disaster management, remote sensing, precision agriculture, topography, construction & infrastructure inspection, delivery of goods, real-time monitoring of road traffic, providing wireless coverage, and extensive fauna census. The challenges encountered for the operational use of drones are multidisciplinary. Thus, the drone system must be reliable, endowed with sufficient flight endurance, and a piloting mode in line with the shot's taking.

Taking high-resolution images and videos using onboard cameras to survey a given target area is a crucial challenge. This helps to evaluate the magnitude of the damage to the infrastructure. The shooting must be planned with a significant overlap between images, without omitting the scene flown over. The drone vision system is often compared to human eyesight, but this machine vision isn't bound by biology and can be programmed to see through obstacles and during the dark.

For drones to be useful in many areas, one must use them in various contexts. In particular, when a drone fulfills a mission in an unfamiliar environment, the question of mobility is essential.

Many flight parameters will influence the result's quality, starting with the altitude and the distance between two flight lines, conditioning the images' lateral overlap. Image processing, which will create three-dimensional models and ortho-image mosaics, must meet the requirements in terms of precision and spectral quality required for the user-defined a priori.

Modern photogrammetry is continuously evolving, and many questions remain about the configuration of these processing chains, depending on the objectives pursued. In addition to their evolving environment, drones are characterized by their autonomy level. Again, each organism often uses the terminology of its own.

- *Evolution under "manual" control*: when the UAV trajectory remotely piloted results at any time from commands sent by a remote pilot in real-time. The human operator continuously controls the UAV system onboard, only from his direct observations. In this context, the UAV does not take any initiative and is dependent on the operator's orders.
- *Evolution "automatically"*: the flight is carried out without the intervention of a remote pilot.
- *Evolution "autonomously":* The UAV fulfills the mission assigned to it without human intervention, within a defined framework, while adapting to operational conditions and their environment.

In light of these different uses, the aerial drone has undeniable virtues. Unfortunately, unconscious or clumsy services tend to channel criticism on this socially and economically useful tool. It is, therefore, necessary to question the relevance of regulating these uses.

Some recreational drones require permission to fly. In all cases, a certain number of rules condition their management. Some areas are no-fly, and others subject to restrictions. Compliance with the legislation in force, typically requiring the drone platform's approval, the remote pilot's appropriate training, and the flight authorization for each aerial mission, are significant constraints on civilian drone deployments.

III. DRONES TO INTERVENE IN THE ELECTRICITY NETWORK

The electricity distribution network's inspection is usually carried out by a series of remote mains tests, checks with binoculars from the ground, and lifting systems. Since the majority of lines are in hard-to-reach environments, current methods are often expensive and time-consuming.

Easy to implement and robust design, the drones will contribute to the security of electrical networks. Much of the current use of drones in the industry occurs in risky and expensive activities, such as inspecting power transmission, distribution lines, and power grids [6].

Working on a high-voltage tower is dangerous. The UAV-based solutions will eliminate the danger for electrical fitters, who do not have to climb the towers.

Due to its size and maneuverability, the drone makes it easy to monitor and inspect electrical equipment in hard-to-reach locations where UAVs can be carried in the back of an off-road vehicle, four-wheel-drive vehicle, or snowmobile. This type of mission can also be performed by helicopters or planes, but the cost argument again proves the drone right without forgetting the ecological benefit. Besides, automated UAVs allow thousands of miles of facilities to be inspected without shutting down operations while reducing the risk of accidents and lowering the cost of their surveillance operations [7].

By embedding an optical camera, thermal camera, and sensors, drones make it possible to capture a great deal of data and take high-resolution snapshots to carry out cartographies or 3D models - in complete safety.

Thanks to their GPS positioning and altitude-keeping system, inspection is efficient and straightforward. Besides, drones can operate in dusty areas and hot, cold, and windy weather, and they can work near a high voltage line. The drone is the ideal tool for power transmission and distribution lines and power grids:

- Much faster than traditional line inspection.
- It is sometimes impossible to access foot (remote, hilly, dense vegetation, etc.).
- The drone avoids having to resort to rope access technicians systematically. Therefore, the safety gain is inevitable.

To simplify and speed up the process of inspecting these power lines, the idea of using drones quickly came to the minds of companies in the energy sector. Given their ability to carry a very high-resolution camera while remaining mobile and precise, drones prove to be perfect allies for this type of mission [8].

Table 1 summarizes some of the smart grid infrastructure inspections using UAVs. More specifically, this table presents various kinds of UAVs used to inspect power transmission, distribution lines, and power grids, and the type of sensors deployed for each application, and the corresponding UAV specifications in terms of payload, altitude, and endurance.

IV. DRONE FOR SOLAR PLANT MONITORING

Due to growing concerns about climate change and carbon emissions, many countries worldwide have increased their investment in renewable energy projects. Solar energy has been one of the most adopted among the different renewable energy solutions available. In the last decade (2009-2019), solar energy investments totaled 1.3 trillion dollars worldwide, representing half of all assets in renewable energy.

Table 1. Smart grid infrastructure inspection and monitoring using UAVs.

UAV Type	Application	Payload/Altitude/Endurance	Sensor Type
MikroKopter L4-ME Quadcopter [4]	Use UAVs for vertical inspection from high rise infrastructures such as street lights	Up to 500 g /Up to 247 m/ 13-20 min.	Laser scanner
Quadrotor, UAV [6]	Inspection of the high voltage power transmission lines	Less than 1 Kg/LAP/ Less than 1 hour.	Color and TIR camera, GPS, IMU
Fixed Wing Aircraft, UAV [7]	Sketchy inspection, identifying the defects of the power transmission lines	Less than 3 Kg /Up to 500 m/ Up to 50 min (50 km).	HD ultra-wide angles video camera
Quadrotor, UAV [10]	Use cooperative UAVs platform for inspection and diagnosis of the power lines infrastructures.	Less than 6 kg /Up to 200 m/ Up to 25 min (10 km).	TIR camera, GPS

A. The Growth of the Solar Energy Industry

Economic factors have played an essential role in the increase in solar energy projects. The installation cost per kW has decreased by 73% in the last decade, from USD 4621 in 2010 to USD 1210 in 2019 [11]. Solar photovoltaic (PV) plant design involves implementing a series of features to achieve the lowest possible cost of electricity.

Solar PV modules are made up of PV cells, most commonly from silicon. Regular inspections of PV modules consist of inspecting each of the panels with a laser temperature gun. After identifying solar panel failures, the operator should record these panels' locations for future repair. Due to the solar parks' dimensions, these traditional methods are inefficient and detrimental to the operation and maintenance teams.

B. UAV-based Solar Inspections

Going underground - before the UAV thermography dawn, it was rarely done on more than 10% of a solar site inspection. In a large solar farm, even 5 MW, more than 26,000 modules are required, and probably two to three technicians to complete the work. Manual thermography is needed when the panel is under the sun, and then the sun is behind the technician, thus casting a shadow. The drone does not suffer from that as it is far enough away. The use of drones in the solar energy industry would greatly benefit.

Drones equipped with thermal measurement technologies help the person in charge to obtain more accurate data and make better decisions.

One of the main reasons for integrating drones in the examination of solar parks is reducing inspection time. Drone integration allows work teams to reduce inspection time by 70% compared to conventional methods.

With the ability to cover great distances and provide high-resolution images, drones have allowed companies from different sectors to carry out safer and more effective operations. Currently, many companies in the solar energy sector use drones to improve their operations' efficiency and increase the quality of service offered to customers. Drones increase the accuracy of solar inspections. Platforms such as the DJI Matrice 210 RTK V2, equipped with thermal cameras such as the Zenmuse XT2, can inspect large areas of the solar park collecting RGB high-resolution thermal images (an example is shown in Fig. 1).

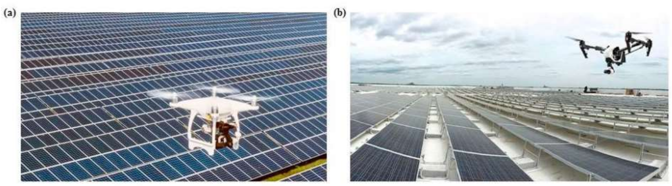


Fig. 1. (a) Quadcopter drone for monitoring solar plant; (b) Tri-copter drone for monitoring solar plant (Source: Gregory Zeller, 2015 http://www.innovateli.com/at-rotor-air-cams-hovering-over-the-future/)

C. *Benefits of using Drones for Aerial Inspections*

Energy inspections usually require thermal cameras, whereas mapping operations require more precision in RTK modules. Aerial images provide a broad perspective on the solar park status and allow maintenance teams to focus on the points that reflect potential failures.

Visual and thermal images provide the fault's precise location, making fieldwork more accurate and less margin for error. Thermal imaging makes it easy to detect defects based on temperature anomalies between cells and panels. By combining the thermal and visual RBG data, the operators can determine if these temperature anomalies result from physical factors such as laminate, cracks, or dust; or if it is due to connection problems such as inverters or wiring faults. The use of aerial images contributes to the improvement in fault detection and helps with the maintenance process.

The information collected by the drones could be stored and organized for processing. Photogrammetry software reconstructs thermal maps from the images obtained. Panel placement is also adjusted using ground control points. After reconstruction and positioning adjustments, the resulting maps are integrated into a Geographic Information System (GIS) where maintenance teams can quickly locate anomalies and rectify them before they have an appreciable effect on production.

Storing records of previous inspections is very helpful in determining the causes of failures. In some cases, a solar cell failure does not justify replacing the entire panel, but it is essential to record these cases to prevent significant losses. Early detection of faulty elements helps prevent inefficiencies in energy production. The faster the potential failures can be detected, the better the response and the lower the probability of significant system failures. Ultimately, a practical inspection in conjunction with a good maintenance plan results in better protection of the investment value and greater energy supply efficiency.

V. Towards Predictive and Application Maintenance

Beyond the inspection and surveillance that identify equipment requiring maintenance, drones can also act upstream and downstream of this process.

Upstream, thanks to their ability to collect data and carry out infrastructure maps at a very high level of detail. Using image sensor-equipped device such as a digital camera, drones can power and enrich the digital twin that requires precise data.

The digital twin is a digital representation of a physical asset that can simulate its operation and performance state. Depending on the digital twin technologies, the simulations predict different behavioral scenarios and make it possible to anticipate risks and anomalies by notably estimating the equipment's lifespan, thus ensuring maintenance predictive.

Drones are also called upon to act downstream of the process, thus ensuring corrective maintenance. Dangerous tasks at height, such as repairing or pruning along power lines, can be left to drones. Enedis, a French manufacturer, launched a project to inspect, renovate, and maintain the electrical grids. Several experiments have taken place: drones equipped with articulated arms have placed "avifauna" beacons (device protecting birds from the risk of collision with electrical cables). Another type of drone was developed by Hélicéo design. This automatic catamaran drone with dual technology of aerial or aquatic propulsion was used to layout the borehole route and run an electric cable. Engineers can thus remotely and precisely manipulate this drone to bury a power line under a river.

A. *Study case: Ice Detection on Electrical Power Cables*

In northern countries, ice storms can cause major power disruptions, such as the one that occurred on the North American ice storm of 1998 that left more than four million customers in the dark with no electricity for periods varying from days to several weeks. In total, more than 20000 electricity poles and 1000 steel towers collapsed under the weight of the ice. 3000 km of Hydro-Québec power lines were temporarily out of use.

Detection of ice formation on power cables can help remove the ice before a significant problem occurs. The detection of objects in images is an ancient theme of computer vision, which has seen impressive progress since the 2000s, thanks to approaches based on the learning of characteristic models of classes of objects. First, descriptors appeared (Haar wavelets, set of points of interest, etc.), allowing the characterization of regions of interest.

Classification methods (AdaBoost, Random Forest, support vector machine, etc.) are trained to detect objects in the areas displaced in the request image's positions.

Since 2010, these approaches have competed with methods based on CNN, whose learning capacities are much more significant due to having substantial learning bases and very powerful computations.

Ice accretion on power cables poses severe risks to the structure. To detect ice accumulation, we first tested many approaches, taking advantage of existing methods, particularly in OpenCV: segmentation by color, detection by gradients or by contours, the combination of classifiers (AdaBoost, SVM) applied to regions of interest or on pixels, etc. These various methods did not achieve the target classification rates in these types of applications, above 80%. However, the CNN classifiers' significant difficulty is that there were no bases available with images of ice accretions on the power transmission line.

A CNN training then optimizes the network's coefficients from a random initialization to minimize the classification error at the output. The two parts of the CNNs are trained simultaneously. According to a gradient descent method, the network's coefficients are modified to correct the classification errors encountered. These gradients are backpropagated through the network from the output layer. With a Region-Based Convolutional Neural Networks (R-CNN) model, each of the proposed areas of interest is received as input by the CNN. Using a Faster R-CNN model, it is the starting image that undergoes this convolution step. It is on the generated feature maps that are obtained the proposals of regions likely to contain the element targeted by the model. This is an improvement in terms of runtime and power required.

In this work, for detection purposes, Faster-RCNN along with ResNet-101 architecture is used. In recent years, it has shown remarkable performance for various classification and detection applications. It utilizes the same traditional network for region proposal generation and detection.

Figure 2 illustrates one example of how Faster R-CNN works. It is also known as a two-stage detection model as it essentially has two stages; the initial stage provides region anchors using Region Proposal Network (RPN). The second stage is employed for electric power cable image classification using bounding boxes and detected regions' information.

The simulation results for ice accretion detection are given in Fig 3.

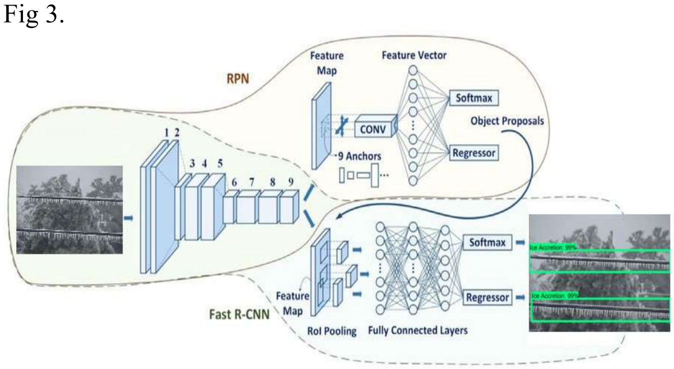
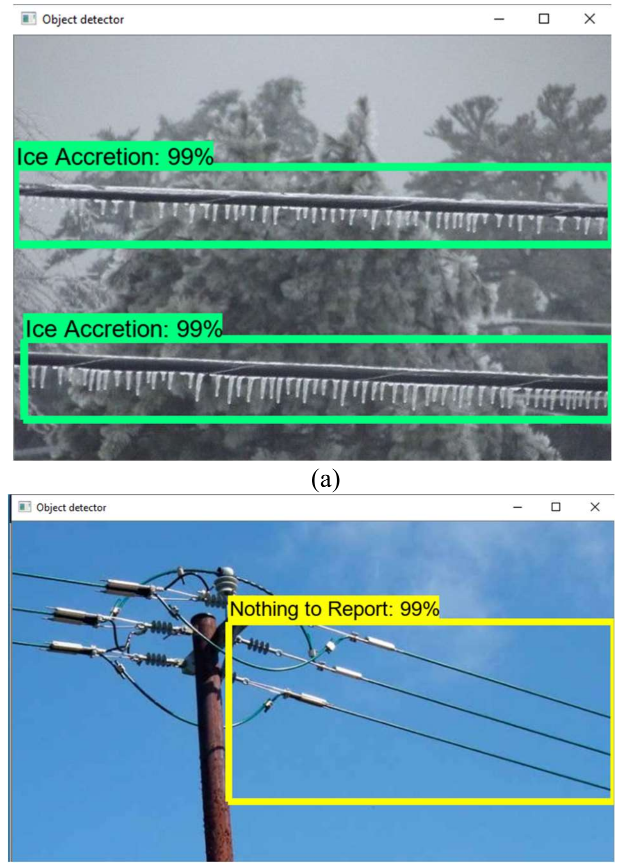


Fig. 2. The architecture of the proposed Faster R-CNN for ice accretion detection. Two sub-networks take images as input and generate separate detections in classification confidence scores and bounding box coordinates.



(a)

(b)

Fig. 3. Ice accretion detection results obtained by the proposed Faster R-CNN, (a) the presence of the ice accumulation, (b) the absence of the ice accumulation.

VI. Predictions for Future Trends

So far, we have been able to have a fairly broad vision of the state of the art of unmanned aerial vehicle technology. Still, its possibilities do not end here, indeed, as it is a technology that evolves exponentially. The research on UAV-based smart grid monitoring is still in its infancy. We are in the first years of its development. We think the next revolution will be substantial for the future of drones. We point out several open issues as further research directions.

- *Drones and Augmented Reality:* Airbus company, from its DAR System (Drones and Augmented Reality for Aircraft Inspections) department, is developing what aircraft safety will be like in the coming years [12].
- *Piloting drones with the mind:* at the University of Florida, the first race of mind-controlled drones has been held, in which 16 university students have participated to pilot the drones through brain-computer interface technologies [13].
- *Drones guided by Artificial Intelligence*: A drone is not autonomous, particularly beyond the line of sight, if it cannot avoid the obstacles in its path and recalculate its route, or even propose a new route, depending on the circumstances encountered. It must carry out its mission in the event of a momentary loss of the satellite link with the ground station. The intelligent drone is characterized by its ability to recognize

topographic data, integrate environmental data (winds, temperature), and integrate information. Researchers from the University of Zurich, in Switzerland are developing new drones to search and rescue lost mountaineers.

- *The AI is useful in protecting the drone:* several researchers are developing AI-based drones capable of detecting certain malfunctions on automatic piloting. It can program the automatic return to base [14].
- *Hybrid drone development:* this is the work carried out by the team of Wang Kangli and Ke Yijie, from the National University of Singapore, who have developed the U-Lion drone as a hybrid model that can take off and land vertically like helicopters and pass to a cruise flight like airplanes. The wings can be fully folded or extended to promote
- *Drones capable of crossing the Pacific:* this is the challenge that the Natilus company has set itself, developing freight transport drones that can autonomously cross the Pacific Ocean. The first drone developed by the company is 9 meters long. Later the company plans to manufacture 24 drones and 42 meters long, covering the route between Los Angeles and Hawaii in about five hours and flying 6000 meters high.
- *Drones that generate electricity:* this is the project that Ampyx Power is developing. These are drones that are kept in the air, over the sea, tied to a rope from turbines, which they pull when the wind pushes to generate electricity.
- *Cardboard drones:* this is one of the initiatives financed by DARPA, the United States Defense Advanced Research Projects Agency, and which is developed by the company Otherlab, to have a new system of disposable drones for the transport of merchandise to be used in high-risk areas or with limited access [15].

VII. Conclusion

Drones have gradually been adopted by the major players in the energy sector, but several challenges remain to meet their expectations. The business opportunity for using drones in the energy sector is impressive, although very few companies have joined in its implementation.

More secure and less expensive than human intervention, drones can replace the inspection procedures traditionally performed by humans.

The drone allows the safe remote overflight of high voltage power lines. Using drones means improved safety and flying continuously and quickly analyzing thousands of kilometers of power cables. Until now, to inspect the power lines of an industrial plant or the networks of high voltage lines, it was necessary to resort.

Drones can restore high-quality and geotagged photos with a powerful zoom, controllable from the ground station. They carry out the visual inspection of cables and isolators' pylons. They allow electric utility companies to pay more attention to repairing identified issues rather than using valuable circuit downtime for troubleshooting. In addition to the safety and cost benefits, the utility industry can now reap the benefits of 3D mapping by using professional UAVs to conduct surveys. Drones can also be used for post-disaster aerial assessment or electrical damage evaluation.

A major technological challenge is to make drones more intelligent to maximize data collection and qualification during their flight.

Research centers are working on drones' automation to improve their mission efficiency despite the difficulties encountered, such as the loss of GPS position or an unforeseen obstacle encounter. The drone must be able to become autonomous in its decision-making. Another issue identified relates to cybersecurity. Indeed, drones' connected world allows data collection, but it poses challenges in data protection. During its flight, the drone emits and receives various signals via wireless communication channels (5G, Wi-Fi, Bluetooth type), which are vulnerable to hacking. This implies increased security to protect the transmitted data, which is critical in the energy sector.

Despite these challenges mentioned, which are far from exhaustive, drones' use is unanimous within the energy sector due to the many benefits. These technologies will bring to electric utility companies, such as infrastructure oversight, lower maintenance costs, and improving human decision-making thanks to increasing data accuracy and reliability. All that remains is to automate the piloting in complete safety!

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