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An Advanced Unmanned Aerial Vehicle (UAV) Approach via Learning-Based Control for Overhead Power Line Monitoring: A Comprehensive Review

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ABSTRACT Detection and prevention of faults in overhead electric lines is critical for the reliability and availability of electricity supply. The disadvantages of conventional methods range from cumbersome installations to costly maintenance and from lack of adaptability to hazards for human operators. Thus, transmission inspections based on unmanned aerial vehicles (UAV) have been attracting the attention of researchers since their inception. This article provides a comprehensive review for the development of UAV technologies in the overhead electric power lines patrol process for monitoring and identifying faults, explores its advantages, and realizes the potential of the aforementioned method and how it can be exploited to avoid obstacles, especially when compared with the state-of-the-art mechanical methods. The review focuses on the development of advanced Learning Control strategies for higher manoeuvrability of the quadrotor. It also explores suitable recharging strategies and motor control for improved mission autonomy.

INDEX TERMS UAVs, quadrotor, iterative learning control (ILC), power-line detection, insulator, high voltage, tracking control, climbing robots, autonomous recharging, wireless power transfer.

I. INTRODUCTION

Electrical power lines are a vital component of the power sector and it is essential that preventive maintenance of High Voltage (HV) transmission lines be carried out in a safer and more efficient way to meet consumer demand. Widespread electrification in the transportation and energy sectors in the coming decades will exacerbate the costs of any power transmission failure. However, overhead electricity lines face numerous problems, including snow accumulation on exposed electrical conductors and constant threats of collapse to the system architecture due to harsh conditions. This typically causes loss of one or more phases [1]–[6]. Transmission lines alone represent between 5 and 10 percent of the total cost of electricity. Significant damage may occur to the Extra High Voltage (EHV) or High Voltage (HV) network; for instance, in France in December 1999, approximately 8 percent of the EHV/HV transmission network was out of action and it took 6 months to complete repairs to the lines. The total cost was estimated to be 150 million euros. However, the economic losses of such prolonged repairs will be multiplied significantly when disruptions are cascaded to more electrified transport and energy systems in future. This could have been resolved more rapidly by swifter identification of faults [7], [8].

In recent years, both climbing robots and unmanned aerial vehicles (UAVs) have been used as automated systems for locating faults in overhead electricity lines, in order to address the limitations of traditional methods. There are challenges in applying such automated approaches, however, due to the structure and components of the system, which comprises power lines, insulators and pylons of various structures. In addition, UAVs are restricted by the non-contact sensing technologies they can use [9]–[11].

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Accordingly, there have been numerous research studies conducted to automate inspect power systems approaches; however, there is a paucity of comprehensive published reviews which highlight certain issues (i.e., maintenance, inspection) for different approaches to the problem [12]–[16]. This is mainly because the technology is still undergoing continuous research and development and there exists no unified framework of applications.

The main contribution of this article is to present a comprehensive overview of the different possibilities, challenges, and obvious limitations and realistic scenarios to improve autonomous robotics in power systems (particularly UAVs) for inspection processes. Furthermore, this paper differs from existing literature by extending the scope of study in the following aspects: this paper (i) covers various major inspection techniques based on autonomous robotics in power systems, namely, traditional operational and environmental methods, electromechanical, UAVs, (ii) reviews the existing iterative learning control approaches in UAVs applications and possibility future trends to used it in inspection approaches, and (iii) emphasizes on the autonomous recharging (i.e., wireless charger from power lines) strategies in UAVs applications to enhance inspection approaches based on robotics.

This paper provides a comprehensive summary of the effectiveness and weaknesses associated with conventional methods as the typical primary solutions used in relation to addressing inspection issues of electric power systems. Then, advanced existing technologies such as robots and UAVs as promising systems are screened and compared. The pros and cons of each approach are adopted in comparison with regard to the judgement of fault points by vision or other methods, data collection, and the problem of trajectory tracking when using both approaches to power system inspection.

Another goal is to achieve high performance trajectory tracking and avoid most of the limitations in the tracking problem addressed in this paper. Since this is a challenging task, it will require more advanced controllers than currently exist, and we propose a new solution based on iterative learning control (ILC) as an approach capable of performing high traceability on the network and coping with weather and exogenous disturbances. In particular, the repetitive nature of power line geometries lends itself to this approach during inspection. In addition, in this paper, a review is conducted on automatic recharging systems for UAV batteries as an essential part of the durability of the work and the extension of the duration of the mission. This has particularly received little attention in the literature, especially for achieving full automatic trajectory tracking and uninterrupted performance on power lines.

The paper is organized as follows. In Section II, it describes the types of fault commonly encountered in power systems, reviews the existing and conventional fault location techniques, and describes their advantages and limitations. Additionally, the quadrotor application is discussed for both vision and non-vision based sensing approaches in Section III. In Section IV, the iterative learning control (ILC) algorithm is discussed and reviewed for UAV applications. Section V reviews automatic recharging system for power line inspection UAVs. Finally, Section VI draws conclusions and provides suggestions for future work.

II. METHODS OF INSPECTION FOR FAULTS ON POWER SYSTEM

In this section, we provide a review of current knowledge about the components of a power system as well as classification of faults which covers the principles of inspections techniques, the most popular methods of inspection faults identified by the Distribution Network Operators (DNOs) and Transmission Network Operators (TNOs). In addition, we introduce the inspections propagation models for UAVs and robot-based approaches.

A. CURRENT METHODS OF INSPECTION FAULTS BY DNOs AND TNOs

The power system components most susceptible to natural hazards are the transmission and distribution lines, which have the most extreme working conditions and are subject to numerous problems. This poses significant challenges for DNOs and TNOs, so it is important to clarify the basic difference between them. The difference lies in these factors: the type of geometric structure, power flow, responsibilities, safety, maintenance, and inspection. In the case of DNOs, a lower voltage and long distance with unidirectional power flow are considered on a local scale. By contrast, TNOs focus on high voltage and long distance by bidirectional power flow of major industrial customers.

An example of TNO challenges, occurs in rough terrains such as mountainous areas in the Liangshan region of China, and the installed system may cause repeated failure in 500 kV transmission lines over a distance of 3 km [17]. This is due to a small error generating a sequence of failures extending long distances until they find a point of failure. The maintenance crew may have to walk as far as 6 km in mountainous areas to determine the exact location of the fault point.

In 2003, power grid outages in the northeastern United States and Canada demonstrated that transmission faults can have a devastating impact on the national-grid, as well as on interdependent systems such as telecommunications networks [18]–[20]. A recent study showed that the failure of transmission lines during winter caused by snow accumulation on aluminium conductor steel-reinforced (ACSR) cable in the area of Jordan caused severe difficulties for the maintenance crew [21].

The complexity of most power grids often makes identifying faults difficult, especially as there are many causes and types of power failure in an overhead transmission line. Examples include storms, lightning, freezing rain and fog, partial discharges (corona), insulation breakdown, short circuits caused by birds or other external objects coming into contact with the line, or tree branches hitting the lines [22]–[26]. These causes are summarised in Figure 1.

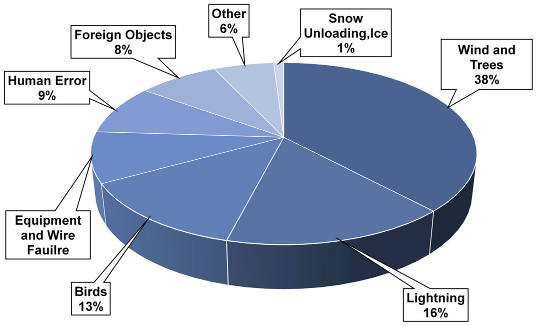


FIGURE 1. **Causes of faults on distribution networks.**

Faults on transmission lines can generate a huge current flow through the cables, unbalance the phases, or generate overvoltages (e.g, back flashover, direct lightning hit to a phase conductor, and lightning-induced voltage) [27]. When a fault occurs, the characteristic impedance values can change dramatically, leading to an interruption in operation of the power system, electrical fires, and various failures of associated equipment.

In a three-phase transmission line, faults can be classified as: single Line to Ground (LG), Double Line (LL), Double Line to Ground (LLG) and three-phase to ground [28]–[31]. Statistics such as those compiled by authors in [31], [32] have shown that LG faults are the most common type in power systems. According to statistics collected by authors in [33], more than 90% of overhead transmission line fault are LG faults. The proportion of LG faults occurring on 220 kV transmission lines is 87.07%; it increases dramatically for 330 kV transmission lines to 98.11%, and is 92.68% for 500 kV lines.

Accordingly, these threats can be divided according to their nature into: chemical, mechanical, and electrical. Chemical damage it is related to corrosion (small holes in the metal), while mechanical damage is related to fractures or damage (ageing or degradation of the equipment). Finally, electricity is related to environmental discharges. Some faults may be avoided through state-of-the-art material design. The authors in [34] pointed out that faults involving conditions such as wind pressure, natural ageing, temperature variation and mechanical stresses on a transmission line in Brazil can be mitigated by designing the system to meet the corresponding mechanical loading demand. Mechanical consideration in the design can be leveraged to avoid serious deterioration due to these effects at the cost of added expense. However, DNOs and TNOs must still monitor cables personally to detect anomalies or malfunctions that may accompany the critical conditions for the dynamic line rating.

The main intent of the inspection by TNOs and DNOs is to check fittings (i.e., dampers and spacers) on an HV power line to (1) find abnormal points and (2) assess the surrounding environment of lines. This enables TNOs and DNOs to obtain a sufficient information access on the failure points. The abnormal points that are recognized through inspection steps include both (i) preliminary inspection and (ii) autonomous inspection [35]. For the latter there is ongoing investigation. In general, the preliminary step is performed through the inspection objects on the HV power line, which are classified into five categories depending on geometric characteristics, position, type, structure, the merits as well as the demerits of these techniques as presented in Table 1.

The most common method to detect line faults is based on visual inspection, which may be conducted via a helicopter or four-wheel drive vehicle, in addition to primitive methods based on the technique of load separation and identifying faults [36], [37]. The studies in [38], [39], and [40] showed that the process of visual inspection may involve getting a complete, continuous picture of conductor behavior as well as thermal imaging (observing hot-spots on lines as indication of fault).

Visual inspection may have multiple aims, including thermographic fault detection with infra-red cameras, visual line inspection with video cameras and insulator fault detection with ultra-violet cameras. Particularly, these methods involve safety risk for the operating crews. Hence the study in [53] outlines the general considerations that must be applied in selecting tools, equipment, and work procedures in a safe and efficient manner.

Traditional methods of detecting location faults are often not economically viable and may not ensure the quality and reliability of the network over time. For example, a comprehensive review in [54] showed that the Ofgem (Office of the Gas and Electricity Markets) and Western Power Distribution estimated the cost of unplanned outages to be over £300 million in Great Britain. This reflects the increased number of disconnection faults based on conventional methods and the probability of faults times and the failure rate and tending to be worse on 132 kV lines.

Consequently, there is a close relationship between the time needed to determine the faults and maintenance strategy, which is critical to the cost. Therefore, the authors in [55] and [56] concluded that life cycle cost (LCC) analysis is useful for customizing the inspection and maintenance strategies which in turn affects the quality of the power delivery and the overall efficiency of power networks. Recently, these concepts have gained even more importance due to increasing pursuit of profit and also the fact that modern policies for liberalization of power and global energy markets may lead to declining reliability levels in electrical transmission systems and stress in operation.

Through the above review, the DNOs and TNOs have been practicing conventional techniques for fault inspection which are based on visual inspection, for a small scale areas (by foot patrol) and larger scale areas (by automobile or helicopter). Trial-and-error switching, highly maintenance cost, long term damage HV lines equipment, manual process and time consuming are considered as major limitations of these inspection techniques.

Due to these problems, a considerable amount of literature has been published on the development of new approaches

TABLE 1. Characteristic rules for current methods of inspection targets in power system.

Object Name	Target	Features location/shape	Task	Techniques	Merits	Demerits	Ref.
Tower (T)	Tower (torsion, suspension, anchor, beeline...etc) (T_1)	Attached to the power line, T shape, Cylindrical structure	The main aims are to inspect the electrical equipment on T_1 (Lightning arresters,..) and structures of Transmission/Distribution	Patrol Crew, Helicopter, Video cameras	Fastest, Quickly and easily reach the tower, Not restricted by region, Ability for long-distance inspection, Unlimited loading of equipment, Contactless sensing methodology	Less safety and security inspection service, Highly maintenance cost, Manual process, Inaccurate, Highly influenced by the operating environment (higher buildings in urban areas, weather-dependent)	[22], [37]
	Overhead ground wires (T_2)	Attached to upper portions of the power line, Line shape	The main aims are to inspect the strands broken by lightning, burnout of T_2 due to the electric discharge	Patrol Crew, Helicopter	Fastest, Not restricted by region, Ability for long-distance inspection, Contactless sensing methodology	Less safety and security inspection service, Highly maintenance cost, Manual process, Highly influenced by the operating environment (higher buildings in urban areas, weather-dependent)	[41], [42]
Line (L)	Phase Conductor (L_1)	Attached to the power line, Curve shape	The main aims are to inspect the cracking/rupture, Broken strand, Detect temperature increase /overheating, Increase of resistance, Check the condition of zinc layer and corrosion L_1	Mechanical devices, (i.e., hot stick), Impedance-based (IB) techniques, Travelling-wave (TW) techniques, Video cameras	Simple implementation, Not complex, live-line working, Contact/Contactless sensing methodology	Trial-and-error switching, Long distance to inspect, Inaccurate, Highly maintenance cost, Damage of object, Time consuming, No sufficient acquisition of information, Requiring measurements with very high sampling rate, Dependent on line parameters estimation, Very limited field tests in distribution networks	[15], [43], [60], [61]
Insulators (I)	Insulators string (I_1)	Attached to the power line, Circle shape	The main aims are to repair and replace electrical devices on Insulators and to detect partial discharge, I_1 replacement	Patrol Crew, Mechanical devices (i.e., ROBTET), Helicopter, Elevators (i.e., Elevator I,II,...), Ground Vehicles (i.e., Four wheel car, Boom Truck)	Short distance, Not Safe, less time, Contact/Contactless sensing methodology	Overlapping due to shooting distance, Effect angle of aerial images by Helicopter, Trial-and-error switching, Damage of object, Manual process, No sufficient acquisition of information, Highly Inaccurate,	[44], [45]
	Insulators unit (I_2)	Attached to the power line, Circle shape	The main aims are to inspect and replace electrical devices on I_2 and to detect partial discharge, Loss of insulation, Electrical flashover, Pinpoint corona and arcing	Patrol Crew, Helicopter, Mechanical devices, Elevators (i.e., Elevator I,II,), Ground Vehicles (i.e., Four wheel car, Boom Truck)	Short distance, Not Safe, Less time, Contact/Contactless sensing methodology	Environmental conditions (i.e., light intensity, weather, and distracting background), Camera stability, Trial-and-error switching, Manual process, Time consuming, No sufficient acquisition of information, Not simple implementation,	[46], [47]
Fitting (F)	Vibration damper (F_1)	Artificial facility Attached to the power line, T shape	Inspection of Electrical Devices (i.e., Break Circuit), Drooping or missing Damper Slipping	Visual inspections, Inspection from ground, Carts, Arm with Blades,	Live-line working, Contact/Contactless sensing methodology, Simple	Unreliable due to potential risk on crews (i.e., live work), Highly maintenance cost, Manual process, Time consuming	[48]
	Clamps (F_2)	Artificial facility Attached to the power line, X shape	Detect broken strands at clamps end, Missing nuts from clamps	Climbing and Visual inspection, Mechanical devices Arm with wrench	Safe, Simple, Contact/Contactless sensing methodology	First breaks occur under clamps and are not detectable, Damage of object, Manual process, Time consuming	[49]
	Spacer (F_3)	Artificial facility Attached to the power line, X shape	Inspection of failures, Defective spacers, Loosened spacers	Climbing and Visual inspection, Mechanical devices, Video cameras	Safe, Simple, Contact/Contactless sensing methodology	First breaks occur under spacers and are not detectable, Damage of object, Manual process, Time consuming	[50]
Environment (E)	Tree crown (E_1)	Under the power line (Large size), Sphere shape, Planar shape, Irregular shape	The main aims are to install patches on the road and to eliminate E_1 around transmission lines, Management of vegetation encroachment and Creeping	Patrol Crew, Ground Vehicles, Mechanical devices, Arm with Blades (i.e., tree trimming),	Safe, Very simple, Contributes to protection from future faults, Economic feasibility, Contact sensing methodology	Highly maintenance cost, Manual process, Time consuming	[51], [52]

to identify fault locations for the purpose of expediting the process of locating faults [57]–[59]. In [60], the authors stated that faults may be divided into temporary or permanent; the former category includes line shorts to earth through tree branches, and the latter includes conductor or pinholes in the insulator. Much research has been undertaken on fault locators and protective relays, which can estimate the location of both temporary and permanent faults. Mechanical damage is not always obvious following permanent faults. Conversely, temporary faults can be cleared automatically if the location of the fault is identified. Thus, temporary faults can expedite the restoration of the line or be estimated with reasonable accuracy [61].

Researchers have been trying to find reliable and efficient ways for fault location identification. The currently available conventional methods in fault location methods can be broadly classified under three headings; (i) Impedance-Based (IB) techniques [62], (ii) Travelling-Wave (TW) techniques [63] and (iii) artificial intelligent techniques [64]–[66]. For these techniques, it is necessary to sense the magnetic field caused by current flows through a cable or conductor. A device such as a fault indicator can be installed either in a substation or on a tower over an overhead electrical transmission line. These have several merits and demerits in use with composed fault location identification techniques [61].

1) IB-BASED TECHNIQUES

The IB methods are widespread among electric power utilities due to their simplicity. Typically, in IB methods fault location algorithms use fundamental frequency current and voltage measurements. Consequently, several approaches are developed based on IB methods such as reactive component (this method is not valid for practical cases) [67], Takagi algorithm (the method was tested in practical transmission line systems) [68] and Girgis method (includes a calculation error due to repetitive iterations) [69].

2) TW-BASED TECHNIQUES

Several studies focus on fault location identification techniques which can use TW techniques. Either the transient created by a fault is captured or impulses are injected into the line and the reflected travelling wave is detected with a time-domain reflectometer. As the fault signal obtained at the end of the transmission line is highly distorted with noise, modern signal processing techniques are required, such as the use of wavelets [63], [70], [71]. However, these methods fully depend on an assumption that the parameters of the transmission line are uniform.

In the above subsection, we have provided an overview of the main traditional methods inspection of power systems. In the next subsection, we will address the limitations of traditional methods and attention will be paid to promising new techniques. Climbing robot-based approaches have been used to produce an automated system in the inspection power system. This is a challenging task due to the structure and components of the system, which comprises power lines (single or bundle), insulators and pylons of various structures.

B. ELECTROMECHANICAL METHODS FOR POWER SYSTEM INSPECTION

The accuracy of judging the fault points in power systems using traditional approaches can be influenced by (i) manpower shortages, (ii) experience of the workers, (iii) tracking process during the inspection, (iv) skipping objects, and (v) hidden objects. The accuracy can be improved by using a robotic approach by following the judgement of fault points by vision or other methods and trajectory tracking when using robots. The following two problems will be reviewed.

1) JUDGEMENT OF FAULT POINTS USING ROBOTS

Robotic devices or climbing robots were first developed for the inspection of transmission lines over two decades ago. Their introduction was motivated by safety factors, the need to access remote and difficult areas and increased operational efficiency. Due to their direct contact with the system, climbing robots have only been designed specifically for a fixed configuration of cable [14], fittings [46] and pylon features [72]. The following papers describe the evolution of climbing robots during inspection and fault points via various methods (i.e. eddy current, vision, thermal), starting with judgement at a single fault point (single power line, or insulators) and then judging the combination of fault points (obstacles and dealing with different cable structures).

A climbing robot that uses wheels to travel along and inspect a single power line was described in [73]. Weighing 17.8 kg, this robot uses eddy current sensors to detect corrosion in live ACSR cables and was developed by Light SESA, a power distributor in Brazil. This method is able to detect the remaining thickness of the zinc layer over the cables, giving a condition judgement on fault points. Specifically, a decrease in layer thickness indicates a fault. However, the downside method is corona interference, which affects (i) measurements, (ii) wireless links, (iii) and electronic circuits.

The robotic device in [74] again focused on detecting corrosion on a single power line via a vision system with a single camera and adding a cleaning option. The difference is that the vision technique detects types of debris (i.e. salt built up on lines, dust, smoke, and polluting winds) that lead to corrosion in [74], while the eddy technique was used to assess the coating thickness and can be applied on wet surfaces [73]. However, the vision system has less data collection and no real-time detection of faults, which in turn reduces the visual data collected on fault points.

Meanwhile, the robot in [75], [76] focused on the thermal method to detect a single power line and add an obstacle fault such as counterweights. The system was equipped with two cameras: a visible-light camera and thermal infrared camera. The objective was to acquire three-phase conductor and insulator data in the case of live lines and apply image processing to highlight expected faults. Furthermore, the robot aims to identify hot spots by distributing temperature on thermal images. However, the incorporation of the thermal method in judging the combination of fault points (three-phase conductors and insulators) also brings along a series of challenging issues related to measurements, implementation, extraction, and identification.

Finally, in [77], the climbing robot operated on live power lines and obstacles to inspect outer-layer broken strand cables using the vision method. The robot is equipped with a Sony FCBEX980S camera with a mechanical part that is able to pan-and-tilt. The main advantage of this method is that it maximizes the rate of defect detection by 99% at the fault point due to its proximity to the cables and camera wide field of view (±360°, ±90°). Furthermore, the measurements are obtained accurately using 26× optical zoom with an adjustable iris. However, the vision method mainly deals with the exposed broken outer layer, while the broken inner layer below the high-pressure points is often overlooked.

It is crucial to note that the studies conducted in [73]–[76] obtained measurements and judgements of fault points only under normal weather conditions (a clear line of sight to operate properly), while the measurements and judgements were performed successfully under very challenging conditions (i.e. windy conditions up to 70 km/h, temperatures from -15 °C to $+35$ °C) in [77].

2) TRAJECTORY TRACKING USING ROBOTS

The following papers describe the evolution of climbing robots, starting with inspection along a single power line, then adding obstacle avoidance, and dealing with different cable structures. Finally, robots with the ability to transfer from the cable to a specific type of pylon are discussed.

A climbing robot that performs power line tracking with a generic controller from a ground based operator is described in [73]. In this tracking system, a simple horizontal trajectory is achieved within a single part between two towers. Furthermore, the robot can correctly track a power line by moving forward and backward. However, the climbing robot is requires a four-person crew to be installed manually on the line conductor using a hot stick. Additionally, this device is incapable of crossing over towers and overcoming most obstacles due to the use of a generic controller and has a maximum line voltage of 350 kV. Moreover, the tracking performance is slow and takes approximately 2.5 hours to achieve the horizontal trajectory.

The robotic device in [74] tackled power line inspection and added the capability to avoid obstacles. Weighing just 13.7 kg, the prototype uses V-grooved wheels to grip the cable and successfully move down a line, passing obstacles such as splices. It was only tested under laboratory conditions and embeds only basic functions: PID control to obtain forward and backward motion via trajectory tracking and an ultrasonic sensor used for open-loop motion control. Additionally, the battery takes approximately 60 mins to charge fully.

Another device, designed by Shanghai University and described in [75], [76], again adds obstacle avoidance and uses a more sophisticated structure to increase its speed. This robot weighs 38 kg and takes eight seconds to move over spacers and counterweights. The structure has two arms with three degrees of freedom, enabling the robot to avoid obstacles by adjusting the arm length. Moreover, trajectory tracking is improved by combining flexible and rigid multibody dynamics theory to avoid obstacles. This sophisticated structure only works with 110 kV transmission lines, however, and moves very slowly with a battery life of 6.0 hours. In addition, this study only considered a single power line.

In [77], the climbing robot's ability is expanded to transfer from the cable to a suspension tower, with the device then moving manually from one side of a tower to the other. The device is controlled by a semi-mobile ground station and was developed by Hydro-Québec TransÉnergie in Canada. Named "LineScout Technology" (LT), this mechanical device attaches to HV cables and weighs 100 kg. The prototype has been tested in field conditions, where it has been shown to overcome a variety of obstacles in an efficient manner.

Unlike the above two studies, the robots in [77] can sustain an accurate tracking performance by tracking two predefined trajectories in two operation modes. The tracking strategy is performed via inverse kinematics and controlling the linear velocities ($\dot{x}$ and $\dot{y}$) and its angular velocity ($\dot{\phi}$), which can be computed in equation 1. By relaxing the problem in this way, the robot can perform the Cartesian mode for trajectory 1 and the joint control mode for trajectory 2 at a defined speed, as illustrated in Figure 2. LT is only semiautonomous, however, and was designed to inspect a single type of transmission line (735 kV). It is also complex and expensive.

$$\vec{\omega} = \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\rho} \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{l_1 \sin\theta_1} & 0 & 0 \\ \dfrac{1}{l_1 \sin\theta_1} & 0 & 1 \\ \dfrac{\cos\theta_1}{\sin\theta_1} & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} \tag{1}$$

where $\vec{\omega}$ is the vector of the joint velocities.

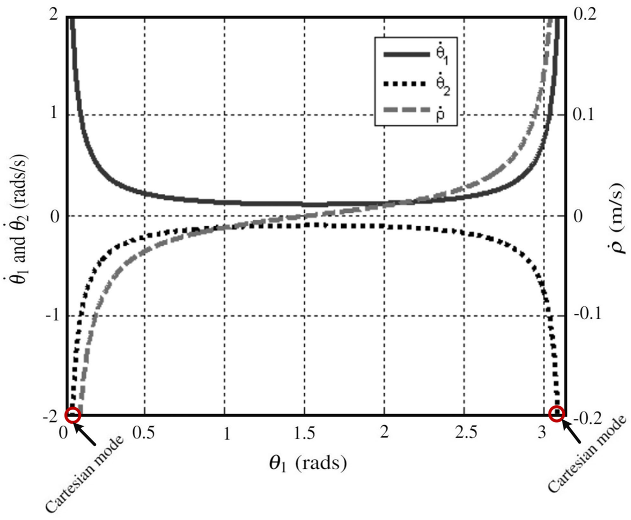


FIGURE 2. Behaviour of joint velocities at input cartesian speed of 0.02 m/s in horizontal tracking.

A similar approach was employed in the design of the ''Expliner'' system, developed by the HiBot Corporation in Japan [47], [78]. In this case, however, the robotic device adds the capability of performing more detailed inspection of bundled conductors. The prototype has a carbon-fibre structure with a T-shaped base and two degrees of freedom, enabling it to travel down live transmission lines while overcoming obstacles in its path. At least seven people are needed to load the Expliner and attach it to a cable, a process that takes about two and a half hours. This operation must be repeated at each tower. It is, however, possible to pre-equip the tower with the clamps, bases and pulleys necessary to lift the equipment, which reduces the preparation time. As well as the cost, time and complexity, this robot is designed only for the specific type of bundled transmission lines used in Japan.

Mechanical inspection robots have, therefore, been successfully implemented on transmission lines and comprise a reasonably reliable method to assess the physical condition of cables. They have significant disadvantages, however – the most sophisticated devices are specialized for one type of HV and are very large, complex and expensive. In addition, they use a balancing mechanism to ensure dynamical stability but this increases their overall weight and makes them very slow. These issues are readily illustrated in Figure 3 [47].

Other important constraints exist. Each robot must be manually attached and can only be used on one section of a transmission line (i.e., between each set of towers). The towers on which the robot is to be installed may only be accessible over very bumpy roads. In addition, live-line installation methods may require boom trucks, helicopters and remote manipulation with insulated sticks. Finally, mechanical shocks during transportation or field installation may damage the electronic boards and key mechanical components. The inability to track the transition between lines and pylons is another fundamental limitation. Furthermore, little work has yet been done to develop additional technologies to enable robots to track bundled conductors, bypass strain pylons and pylon/line docking.

In the above subsection, we provided an overview of power system inspection using robots, including 1) the judgment of fault points by vision or other methods and 2) the problem of trajectory tracking. In the next section, attention will be given to new promising UAV techniques in power system inspection. This is a challenging task due to the structure and components of the system, which is composed of power lines, insulators, and pylons of various structures.

III. DETECTION OF UAV POWER SYSTEM

The emergence of UAV technology has the potential to address the aforementioned limitations due to their inherent advantages of cost, manoeuvrability, speed, and ease of setup. They also do not require contact and can attain the required heights and positions needed to perform major inspection tasks. UAVs can also be operated in more severe weather condition and can operate in places that are either dangerous or unreachable for humans [79]–[82]. This section reviews the approaches employed in this area, which are generalized to the specific problems of those focusing on the inspection of fault points (i.e. power lines, pylons/insulators, and combinations of those points), those focusing on data collection, and finally, those focusing on tracking control of UAVs.

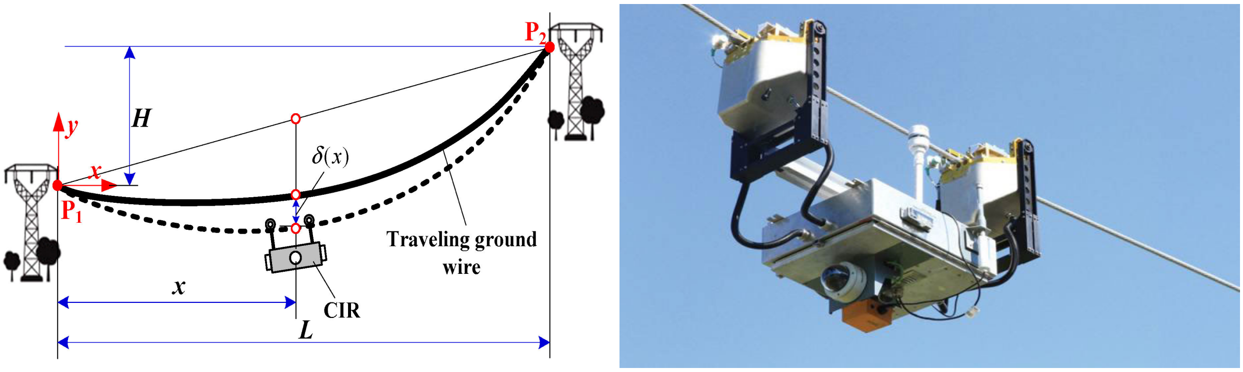
A. DETECTION OF FAULT POINTS

This subsection reviews the approaches employed in this area, which are classified into those focusing on detecting fault points solely on a single component (a single power line or insulators) and then detecting fault points on the combination of components via various methods.

The study in [83] used a UAV with thermal imaging to inspect joints in power lines by analysing their temperature, thereby avoiding costly service interruptions. The study showed that relevant temperature anomalies can be detected in the electric lines and devices. Even from short distances, however, it was impossible to achieve accurate temperature measurements of the electrical faults. The helicopter system in [84] similarly used thermal imaging to inspect joints in power lines, but focused on long-distance qualitative inspection. The results showed that the joints have a higher temperature than other parts of the towers and can be detected as hot spots in thermal images. However, the accuracy achieved in both the studies was poor due to the large measurement spot size compared to the small target size, as well as the long measurement range, object reflection and weather conditions. Furthermore, neither study provided an in-depth analysis of their results. Although this inspection method allowed access to hard-to-reach locations and increased inspection speed, it had many disadvantages. Because the helicopter was manually operated and used to process raw data, extraction was less efficient and produced lower-quality data.

A smaller quadrotor was developed in [85] to again detect faults on power lines, now using remote sensing spectral-spatial methods. The UAV was manually launched to find fault over a single cables from the ground. The UAV weighed 1.5 kg and was fitted with a GoPro HD Hero2 camera used for inspection. This was different from [83] and [84], which adopted a thermal method together with crude image processing (means poor quality of the inspection). The study in [85], considered both the K-means algorithm and Expectation Maximization (EM) to classify the pixels into the power lines and non-power lines. This enhance the quality of detect faults rather than the thermal method in [83] and [84] were unable to detect faults on single power lines with high accuracy due to the presence of (1) heat absorbing (2) and emitting sources in the environment, leading to lower temperature variance among the power lines and background (non-power lines).

The UAV in [86], meanwhile, focused on the inspection of medium-voltage power lines using vision based methods. This type of line has increased height and distance compared to a distribution (low voltage) power line and requires a strain tower rather than a suspension tower. This provides a greater challenge, due to the additional supports of the strain tower. Accordingly, a bigger UAV platform was selected in



(a) Additional sag of walking ground wire.

(b) CIR climbing robot is walking through ground wire.

FIGURE 3. Cables subject to additional sag with function, $\delta(x)$ due to additional weight of climbing robot. To express the sag various factors are taken into considered: suspension points (i.e. P_1 and P_2) on tower, cross-sectional area of cables, L as horizontal spacing, horizontal stress of power line, and impact effect. This impact effect represents vibrations from robot and wind (left) and robot on double 315-kV circuits (right) [47].

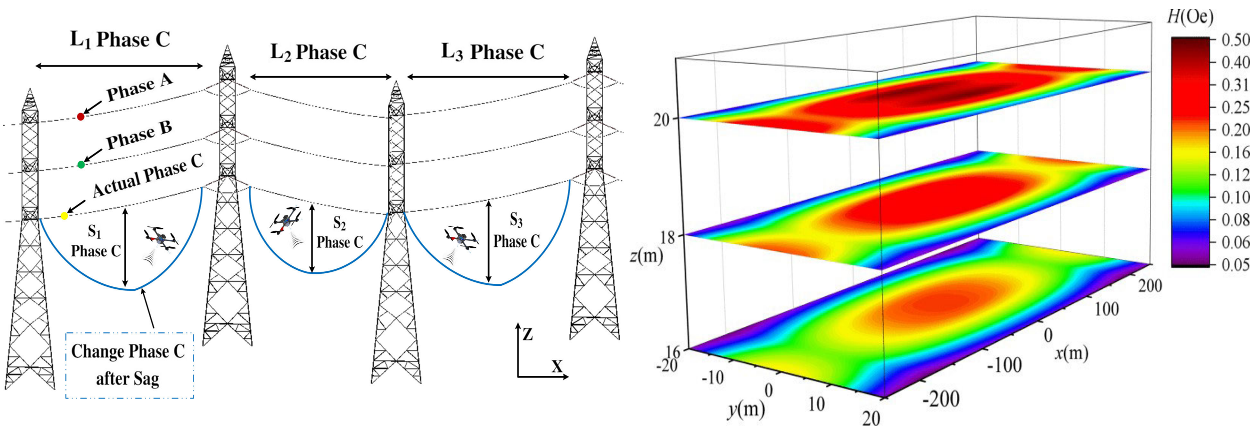
the form of a V-TOL Aerospace BAT-3. Camera-based image processing was used to capture data. First, a filter based on a pulse coupled neural network was applied to remove the background. Then, straight lines were detected using the Hough transform. Finally, spurious linear objects were eliminated using the K-means clustering approach. These approaches focus on the detect of fault points for power lines only. However, they have many drawbacks, such as low speeds and inaccuracy. Although, the images were satisfactory, the overall system lacked accuracy and speed due to the trade-off involved in selecting a more sophisticated vision system at the expense of a rather simple control structure.

The UAV in [87] again focused on detecting faults of the high-voltage overhead transmission lines using vision system, but used a large size fixed-wing UAV system to demonstrate feasibility in different application scenarios. The system was equipped with a 6RQ/I-6000 camera and GoPro Hero 3 camera to capture both visible light images and video. In addition, the UAV had a maximum load capacity of 30 kg. Due to its large platform, the distance from the landing point to the destination power line occupies 15% of the whole flight. It also has many other limitations, such as low speeds and inaccuracy. This kind of inspection requires the helicopter to travel slowly and stop at every tower without detecting it, resulting in a considerable increase in the inspection time (and cost). This was due to the use of a large UAV and the attempt to avoid the influence of magnetic field and harmonic distortion component from the power line.

Similar to the above, the UAV in [88] was used again for detecting three-phase faults on a 500-kV high-voltage overhead transmission line system, but used a small commercial platform. The method can identify fault in cables via reconstruction between the transmission line current and the surrounding magnetic field distribution. Compared with [87], the study in [88] conducted a scaled down indoor experiment that aims to consider the influence of the magnetic field during fault point detection. Furthermore, the platform contains a TMR magnetic field vector sensor to obtain the data distortion and magnetic. Moreover, the experiment demonstrated that the measured magnetic field through five continuous spans led to an irregular magnetic field due to sag of the conductors as illustrated in Figure 4. In this study, the problem of the magnetic field fluctuation that accompanies transmission lines is omitted, especially during power outages. In this case, a new problem arises.

The next group of papers considered the inspection of insulators. An unmanned helicopter was used in [89] based on vision system to detect faults on many insulators that appear on the travel path in a medium power transmission line system at 11 kV. In addition, using theoretical techniques, many attempts were made to determine the camera and lens combination that would provide the best quality images of faults. Ultimately, a Canon 5D Mark II SLR camera with a 105 mm focal length was selected for optimal performance. The results, however, showed that a large camera is always needed to obtain high accuracy. For example, to distinguish the metal pins on the insulator, a 200 mm focal length is needed, resulting in a camera weight of 1210 g which is both massive and expensive.

The UAV in [90], meanwhile, focused on inspecting fault points on insulators in high tension power lines while applying Faster R-CNN (Region-based Convolutional Neural Networks) as a way of reducing the costs involved in inspecting and maintaining Dead-End Body Components (DEBC) (a full tension device that is used to attach the conductor structure to the insulator string). In the UAV's test flight, images of the live high-voltage power lines were collected by flying the UAV approximately 15–20 m from the imaged DEBCs. In addition, a sensor comparable to the Sony NEX 7 was used for data collection. These data were processed through simple image techniques, which served to augment 146 input images to create 2437 training samples. The system was tested on 111 aerial inspection photos, and achieved 83.7% accuracy and 91% precision. The detection accuracy and precision



(a) Schematic diagram of transmission line system during 3 spans. **(b)** Distribution of magnetic field for Phase C during various spans [94].

FIGURE 4. Height of phase C is subject to different vertical spacing sag *S*, which reflects varying over spans *L* in horizontal spacing which in turn lead to irregular magnetics with different heights for Phase C (left) and influence of irregular magnetic field distribution on horizontal xy-plane, where $\dot{H}$ is vector of magnetic field generated by one-phase transmission lines starting from heights of 20, 18, and 16 m (right).

were increased to 97.8% and 99.1% by adding 270 additional training images and including a new insulator class. Both [89] and [90] were only interested in the inspection of insulators rather than the other system components, such as cables and power pylons. They focused on improving the accuracy of camera solutions to allow objects at a distance. This need arose because the UAVs reviewed so far only used basic, generic controllers, meaning that a sophisticated camera was necessary.

The following papers expand the UAV scope to attempt detection of the fault points on the combination of components.

The UAV in [91] was loaded with LiDAR and had a camera with a resolution of 1280 × 1024 pixels. Both measured the correct distance to the power line. At a distance of 10 m from the power line, however, the line appeared as a 1 pixel wide ridge in the image as shown in Figure 5. Additionally, the results showed poor accuracy in terms of the appearance of the 35 mm power line thickness versus the viewing distance function, as illustrated in Figure 6. ACSR cables appeared as a small line with insufficient detail to distinguish faults due to the reliance on traditional control approaches.

The paper in [92] employed a DJI Matrice 100 quadrotor platform that was equipped with a pan-and-tilt camera and two advanced embedded processors (NVIDIA TK1 and NVIDIA TX2). The paper suggested a Faster R-CNN due to its light computational cost and good accuracy to detect and inspect power components. The UAV attempted to detect faults using two cameras: one to follow tower to tower and the second to follow from tower to lines. Furthermore, these deep-learning-based detection algorithms were trained and tested through a total of 1280 sheets of images. For this study, however, the first challenge was limited to one type of learning algorithm, thus compromising the accuracy of the detection. The second challenge exhibited poor performance in detecting small objects. This is a significant problem since many of the important power components (such as insulators) are very small compared to others (such as poles).

FIGURE 5. Images of power line taken at closest distance during landing mission. As UAV descends, thickness of the power lines reaches first 1 pixel in width (left) and 50 pixels in width at the end (right) [91].

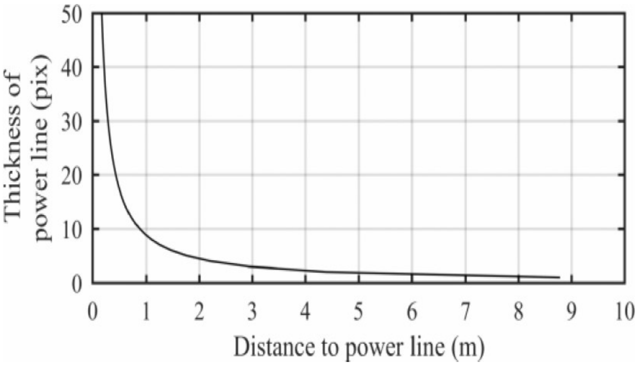


FIGURE 6. Camera resolution effect with 1280 × 1024 pixels on distance estimation. At a distance of approximately 8.8 m, theoretical thickness of 35-mm power line reaches 1 pixel [91].

Finally, in [93], a large unmanned helicopter was used to perform a full and autonomous detection of fault points of overhead transmission lines, pylons and insulators. This large helicopter was equipped with a multiple sensor platform (LiDAR, thermal camera, ultraviolet camera, short-focus camera, long-focus camera) to acquire information about power line components and surrounding objects. The experiments were carried out on a 4.2 km long transmission line, with 13 towers and 78 insulators, at Qingyuan in Guangdong Province, China. However, using multiple sensors proved to be a good solution for full inspection for both insulators and cables but the additional components increased the weight and cost, as well as complexity, of the UAV system.

Most attempts were costly and lacked a sufficiently close control of speed and other physical parameters to enable the collection of higher quality data. Significantly, the studies neglected the role of control systems, which meant that data collection was regularly abandoned due to the time limit built into the algorithm. The next subsection will review the data collection.

B. DATA COLLECTION

Operating autonomously in complex environments without external inputs from humans requires that the UAV integrates perception, learning, real-time control, reasoning, decision-making and planning capabilities [94], at least to some extent. In the past decade, significant improvements have been made to this aspect of the autonomy of UAVs. As discussed, a primary area of quadrotor use is the acquisition of information over a defined area [95] to reduce outage. Examples in this area will now be examined, as they are relevant to the potential use of quadrotors for HV overhead power line inspection. Here, examples include environmental monitoring by scanning wooded areas for fire prevention [96], inspection of industrial plants [97], agriculture, surveillance and weather observation [98]–[101].

We present this area of acquisition of data using different types of sensor technologies by grouping them as either (i) Non-Vision Based, or (ii) Vision-Based. We also provide a review of available studies for inspection of power infrastructure based on vision sensing, as it is a less explored field. Furthermore, we highlight the level of autonomy in the UAVs used by the works as shown in Table 2.

1) NON-VISION BASED APPROACHES

Typically, the main path planning task for an autonomous flying UAVs is to reach a desired location in an uncensored manner, for example without human interference. At present, there are several effective systems for indoor, and outdoor navigation of UAVs. The study in [102] involved a quadrotor platform and focused on outdoor operation by using the non-vision approach. The application of this system was performed outdoors and had the benefit of utilizing a global positioning system (GPS) and IMU measurements. The UAV platform in [103], achieved the same performance using different IMU.

Similarly to [103], the authors in [100] examined the same approach to enable UAVs to perform remote sensing for an agriculture application. The considered problem was solved by GPS to give the UAVs information about their location and height. However, the major drawback with using GPS is that signals may be lost in indoor environments and most urban areas and it is not always possible to acquire adequate signal strength [104]. A UAV with GPS cannot immediately sense its environment, but only receives the height and position relative to known general parameters. Consequently, in practice, these strategies are not effective for inspection of power infrastructure. A UAV with GPS cannot immediately sense its environment, but only receives the height and position relative to known general parameters. This means that problems frequently happen when the environment changes rapidly and unpredictably.

In the similar context, the study in [105] also focused on an autonomous flight of quadrotor by employing another non-vision sensor (a laser range finder). In [106], the authors attempted to provide solutions to aid a quadrotor UAV to land on an unknown surface based on a laser range finder sensor. It is shown that the laser system can give a plausible measurement of the inclination of a surface that is variable with time in order to suitably design a landing trajectory. Thus, the system is able to track the surface angle during the transition to zero incline. Both of the works aim to provide range measurements for obstacle detection during take-off and landing.

Again, in [107] and [108], the authors expanded to controller manoeuvres such as taking off and landing by integrated non-vision sensors but this time by adding a filter for estimating, in real-time, the roll, pitch, and yaw angles based on gyroscope data. Due to lack of performance, the authors in [109] proposed the use of a retro-feeding controller based on quaternions for more stability during taking off and landing. The authors in [110] suggested that the use of an intuitive strategy based controller could improve stability in take-off and landing. Based on this solution, signal processing and gyroscopes can mitigate some of the limitations of the IMU.

Other works also confirm that height sensors are critical to altitude stabilization. In [111], four SRF10 ultrasound range finders were used to achieve altitude control and obstacle avoidance. It was found that having the sensor pointing straight down achieved satisfactory control. Reference [112] aims to achieve altitude stabilization fora quadrotor by using (i) 3D telemetry (to communicate with the ground station), and (ii) an ultrasonic sensor (to measure the height). This adds more weight and cost to the quadrotor platform due to the addition of an Arduino board, micro-controller and ultrasonic sensor.

2) VISION-BASED APPROACHES

Vision-based automatic methods are attractive because they have the advantage of not requiring any special equipment, as only a camera and a vision processing unit are required. There is currently much research into vision-based systems for UAVs. The vision techniques may be classified based on vision sensor configuration into; (i) monocular (using one camera), (ii) stereo (using two cameras). The advantage of stereo vision is that it can be used to measure a distance whereas monocular vision cannot. Thus, when image is captured in three dimensional (3D) space, any information of distance in the image projection is lost. This is because 3D space is projected onto an image plane, which is in two dimensional (2D) space. However, if two cameras are used it is possible to create solutions using a depth map which retains this information. In the following, we review the monocular vision, then stereo vision strategies.

Although the monocular vision is not as diverse as stereo vision, research efforts in landing applications often focus on monocular vision. Thus, the authors in [113] and [114], adopted the monocular vision in order to estimate and stabilize the quadrotor's orientation. Similar to [113] and [114], the authors in [115] also focus on monocular vision, taking off and landing applications for a quadrotor platform. The difference is that the landing involved using a SRF10 ultrasound range finder. In addition, computation time is the main concern with monocular vision, even though this form of vision requires only half the amount of processing when compared with stereo vision.

The authors in [114] and [125] attempted to provide solutions to handle computation time with monocular vision. In the first approach [114], the authors suggested a wireless link to communicate with a base station where image processing is performed. Then, based on the obtained results, the amount of data transmitted is minimized by running certain processing applications on-board the quadrotor to limit the size of the image transmitted. However, there is significant impact from wireless interference between the quadrotor vehicle and surrounding areas. In the second approach [125], the authors used a separate on-board microcontroller to send parameters to the main control board of the microcontroller through a wired serial link. It is shown that the proposed approaches guarantee a feasible solution. Moreover, the second approach offers a greater advantage of preventing the quadrotor from remaining within the range of the base station.

As opposed to the above studies, references [126] and [127] considered stabilizing a quadrotor by using stereo vision. In [126], the study aims to obtain stability of roll, pitch and yaw for accelerometers, gyros and a compass. In fact, the system used the stereo vision system to provide additional information to the quadrotor about its horizontal and vertical movement in relation to the target seen. However, the main drawback was the computationally intensive algorithms which need to be done on a computer with the control parameters then sent to the microcontroller on the UAV.

Reference [127] proposed a technique combining optical flow measurements with stereo vision information (stereoflow) in order to obtain a 3D map of the obstacles within the scene. However, the combination of stereo and optical flow is more significant to navigate in urban canyons compared with the technique based on just one vision sensor. Another related work is [128], which presented a technique for path planning with stereo-based vision that may allow UAVs to navigate safely in external environments while performing tasks such as HV line inspection. However, the system failure rate was high because the stereo-based techniques specifically designed for this application are unlikely to detect thin obstacles such as transmission lines.

In Table 2, we have systematically grouped some of the most recent applications of vision based UAV technologies for power system inspection. In general, vision-based approaches are potentially useful for inspecting and data acquisition in all related works. As previously reviewed, the performance of UAVs for inspection can be demoted due to 1) vision-based approaches, 2) not respecting payload constraints and 3) using inaccurate generic control system, which impacts the level of autonomy.

This will develop UAV technology to address the aforementioned limitations of monitoring and surveillance of power systems. It will utilise the potential manoeuvrability of UAVs in this area, where hitherto little attention has been paid. It will seek to produce high-performance solutions for automating tasks in inspection, monitoring and identifying faults on HV electricity grids. Since this is a challenging task, the next subsection will review this area.

C. TRACKING CONTROL OF UAV

For inspection missions, the UAV aims to fly autonomously near fault points by the optimum trajectory. To obtain successful inspection for fault points, trajectory tracking is considered in controlled trajectories of the orientation angles and position, velocity error, and obstacles. This subsection reviews the control approaches to solve the trajectory tracking problem during the inspection of the power system. The following subsection review this area, starting with power lines (horizontal trajectory), pylons/insulators (vertical trajectory), power lines to power lines (transition and horizontal trajectory), and pylons/insulators to power lines (vertical, transition and horizontal trajectory), which constitute all possible tracking motions during the inspection of UAV power systems.

In [84], trajectory tracking for a quadrotor system was designed only for the altitude control problem scenario using PD control and represented the basic scenario. In this scenario, after take-off, the quadrotor tracks a reference trajectory (simple vertical line) representing ascending and descending. However, the results did not demonstrate any concern about the effect of extra payload, which impacts the time and thrust required to achieve trajectory tracking, or the extent to which external disturbances affect simple tracking performance.

According to [85], the UAV again focused on tracking power lines, and the horizontal trajectory performed poorly through manual control with simple proportional integral derivative (PID) in the presence of the radio noise emitted by the power lines. It is noted that the horizontal tracking performance was sluggish and had low accuracy, and thus, it was compensated by tracking from different altitudes and different angles with 11 attempts. This solution was relatively acceptable, as the power line was a three-phase 220 V with

TABLE 2. Application of UAV in vision-based for power infrastructure.

Vehicle type	Infrastructure	Sensors/tech.	Weight	Output	Limitations and level of autonomy	Ref.
Helicopter	Power line	Stereo rig	–	Image	LQG controller for Roll and Pitch, while a PID for Yaw, Task level autonomy (For one or more task in Infrastructure)	[116]
Ducted-fan	Power line	Camera	25 kg	Image	Consists of two cranked link to power line, Only work with same physical Configuration of power line, Conditional autonomy (Assistance and Supervised)	[117]
Simulation, no platform	Power tower	–	–	Image	No experiment have been done here, Conditional autonomy (Assistance and Supervised)	[118]
–	Power tower	–	–	Image + tower	Manual control, No autonomy (Human function)	[119]
SmartCopter UAH	Power line	Stereo vision, laser scanner	12.3 kg	Image + track	GPS based, The structure limits its flexibility and makes it challenging to stabilize, Conditional autonomy (Assistance and Supervised)	[120]
CAS Quadrotor	One side of power lines	Monocular-based	2.7 kg	Image	Data garnered is sketchy, Small flight time, Conditional autonomy (Assistance and Supervised)	[121]
ZN-2 UAH	Power line	visible-light camera, infrared camera,	7 kg	Image + thermal	Gas engine based UAH, Quick inspection, Conditional autonomy (Assistance and Supervised)	[122]
–	Insulators	Monocular-based	–	Image	Manual control, No autonomy (Human function)	[123]
–	Power line	Camera	–	Image + track	Aims to identify the necessary parameters and system components for only monitoring power lines, Task level autonomy (one or more task in Infrastructure)	[124]

a low height. However, this provides a greater challenge on transmission lines with a large height.

Similar to [84] and [85], the authors in [116] attempted to solve the horizontal and vertical trajectory and attitude control problem of a UAV in a power line by proposing position tracking for the outer loop and attitude tracking for the inner loop. To perform this, the linear quadratic Gaussian (LQG) was used for roll and pitch and a PID for yaw. It is a useful technique and performs well for achieving trajectories over power lines. Furthermore, validation in the presence of external disturbances was tested indoors by pulling the UAV with an attached cable.

However, both studies [84] and [85] used generic control to perform horizontal and vertical trajectories, which have a low impact on the tracking performance in terms of the time and thrust required to achieve faster tracking. Additionally, no state or disturbance observer is used to estimate the external disturbance, so the UAV still only performed basic scenarios for the tracking system. It is important to note that studies in [84], [85], and [116] were not dedicated to the acquisition of dynamic line parameters which is also important to maintain the UAV's track and safety. This poses an important challenge in implementing technology.

To accommodate dynamic line parameters in trajectory tracking, the study in [88] employed a nonlinear optimization problem for the position and current parameters of the lines to achieve a favourable trade-off between system performance and complexity. Moreover, the authors proposed a novel parameter reconstruction method for overhead transmission lines to maintain the UAV's track and safety. In addition, theoretical simulations indicated that this approach can perform real-time transmission line monitoring and UAV trajectory control. However, the study included the following limitations: (i) no accurate control methods were used for UAVs in the presence of magnetic field interference (when a shunt fault occurred) to prevent trajectory deviation, and (ii) the experiment was conducted in a laboratory environment.

Different from the above studies [83]–[88], the research efforts in [89] and [90] focused on tracking insulators. The UAV in both studies adopted generic control as its main system to track over the travel path in a medium power transmission line at 11 kV. This tracking system is generated for basic scenarios (vertical flight until reaching a distance of 20m from the tower) with a ground control system. Both [89] and [90] were only interested in the inspection of insulators rather than other system components, such as cables and power pylons. Moreover, the control experiments were implemented on one segment of a trial transmission line. This need arose because the UAVs reviewed thus far only used basic, generic controllers.

The following papers expand the UAV scope to attempt the transition from one HV power line to the next, with the UAV launched manually from the ground tower. In [91], the UAV operated within between 6 and 10 m of a live line, then transitioned over the HV power lines with a rating of 315 to 735 kV to skip the tower and detect the cable only. Due to the challenges of this planned travel path, the base frame of the UAV was modified to weigh just 14 kg. In addition, the system was complex and very slow during this transition, and required a significant amount of hardware.

The UAV described in [92] focused on transition from tower to tower, then from tower to HV power lines. It attempted to resolve the problem of continuous and robust navigation along one side of overhead transmission lines. This paper suggests integrating tracking and kernelized correlation filters (KCFs) for light computational cost with real-time and reliable transmission tower localization. The inspection trajectories are introduced in Figure 7, where the UAV starts performing a trajectory 1 (from point A until the reach at point C). Then, trajectory 2 is performed from B to C with a sub-interval of the transition setting to the next point D.

In most conditions, however, the tracking suffered from a serious drift, which impacted the inspection. Since this happened due to a lack of prior knowledge of the object, the paper tried to resolve this by combining the tracking with deep learning-based detection which could be trained in advance over many samples. This learnt knowledge could be used to re-initialize tracking when drift occurred. Another fundamental limitation lies in the fact that the UAV was unable to charge and land automatically during this transition.

Finally, in [93], a full and autonomous inspection of overhead transmission lines, pylons and insulators was considered. This paper adopted a double-closed loop control method to achieve automatic target tracking. The outer loop employed a distance control method, enabling the UAV to start tracking when was close enough to the task point. The inner loop employed an attitude control method, which used to calculate the heading and the pitch angle. This method had to be completed within a time limit, however; if it was exceeded, the task was abandoned and the UAV moved to the next task. According to the outer loop control, the UAV is unable to satisfy the conditions to implement the tasks and has low performance. Basically, if the distance between the UAV and the fault point is shorter than the distance threshold D, then no track occurs. Significantly, this inaccurate control method impacts the tracking performance and imposes a higher operating cost.

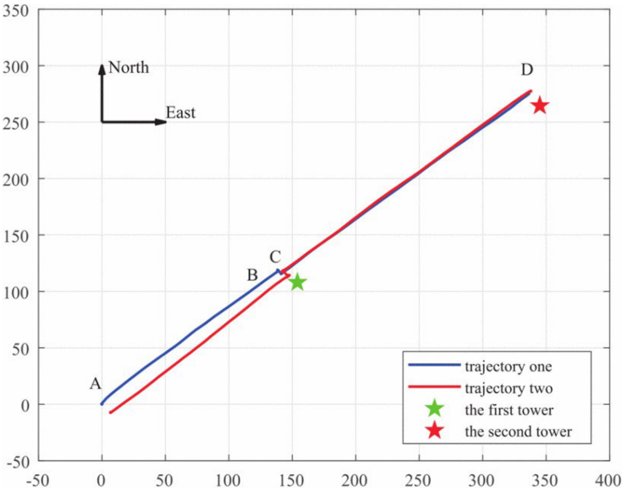


FIGURE 7. Inspection trajectories in planar view with a flight velocity of 1 m/s [92].

In Table 2, we summarize a comparison of the different UAV applications in the inspection power system according to the size of the UAV, object for tracking, level of power, system extra payload, external disturbances, and tracking performance.

D. SUMMARY AND DISCUSSION

This review has summarised the many attempts to use UAVs to automate inspection for conductors, pylons and power components. None of these methods, however, have been able to demonstrate accurate inspection of the complete system in an autonomous manner. This is due to the following factors:-

Firstly, most of the attempts consisted of task-specific approaches for the inspection of power lines, insulators and transition, respectively. For power line inspection, the results showed that the UAV either needs to fly relatively close to the lines to take detailed images of the physical condition of the conductor or farther away, but then to use additional sensors and larger cameras, which required larger, heavier, more complex, and thus more expensive, UAVs.

Secondly, many attempts have been made to identify broken insulators but have not been able to inspect autonomously. While they are capable of inspecting basic power components and results have shown that high quality is possible using non-contact sensing, expensive equipment and fine control of the camera are required.

Finally, the transition task has received less attention and it has proved challenging to move from power line to pylon and from line to line. Implementations have been very slow, complex and have needed a lot of hardware. The major reason for this is an absence of sophisticated and intelligent control. In addition, the UAVs' ability to land and charge during this traveling path has been largely neglected.

This review has shown the potential for the use of UAV-acquired data for fault detection. Current limitations, however, can only be addressed by (i) more accurate motion control, (ii) faster flight times, (iii) the ability to perform

TABLE 3. Comparison of different UAV tracking controls in detecting power system.

Size of UAV	Object to tracking	Level of power system	Extra payload	External disturbances	Tracking performance	Reference
Large	Power line (Horizontal trajectory)	Transmission (Large distances, High altitude)	Yes	NO	Poorly performance Parameter uncertainties, Controller tolerance to noise	[84]
Small	Power line (Horizontal trajectory)	Distribution (Short distances, Low altitude)	No	No	Poorly performance, Low accuracy, Generic control, Consumes energy	[85]
Large	Power line (Horizontal trajectory)	Transmission (Large distances, High altitude)	Yes	Yes	Good performance but Less stability while encountering disturbances	[86], [87]
Small	Power line (Horizontal trajectory)	Transmission (Large distances, High altitude)	No	No	Indoor experiment	[88]
Large	Insulators/Pylons (Vertical trajectory)	Transmission (Large distances, High altitude)	Yes	Yes	Poorly performance, Generic control	[89], [90]
Large	Combination (Transition)	Transmission (Large distances, High altitude)	Yes	No	Parameter uncertainties, Very slow tracking	[91]
Small	Combination (Transition)	Transmission (Large distances, High altitude)	Yes	Yes	Good performance Trajectory 1 (fast tracking) Trajectory 2 (slow tracking)	[92]

automatic transition tasks, (iv) the acquisition of data from more than one type of sensor and (v) the ability to charge and land automatically. To address the existing limitations of current UAV-based inspection for HV systems, the next section will review the applications of UAVs in data collection that has potential to address the pressing problems outlined above.

Since this is a challenging task, it will require more advanced controllers than currently exist. In particular, since the inspection is inherently repetitive, this motivates the development of Iterative Learning Control (ILC) based algorithms for high performance tracking.

IV. ITERATIVE LEARNING CONTROL IN UAV APPLICATIONS

The iterative learning control concept refers to the repeatability of operating a given objective and the possibility of improving the control input over previous operations (i.e. trials, iterations, and passes) through learning. In addition, ILC is an approach to improving the transient response performance of the system, which runs frequently over a specified period of time until accurate tracking is achieved. Moreover, the ILC approach is usually called recursive online control because it (i) requires less calculation and (ii) requires less prior knowledge about the system dynamics. In the last 20 years, iterative learning control has continued to evolve at a fast pace, especially in quadrotor applications.

Their application was motivated by the proven inherent advantages of past work, which include increased accuracy and robustness in case of uncertainties and external disturbances. The following sections describe the significant potential of iterative learning control in UAVs applications, and can be grouped in three categories, starting with basic ILC forms, then ILC in combination with different control approaches. Finally, UAVs to achieve high performance with the more general ILC forms available are described, with a focus on those that have been applied in practice to engineering systems, which bears a particular focus in this paper.

Iterative learning control was first proposed in 1978 by Uchiyama [129], however, as this paper was written in Japanese, it did not receive significant attention outside Japan. In 1984, Arimoto proposed the first learning algorithm and ILC has since been applied to many fields, including robotics [130]. This defines ILC as a novel control technique applicable to systems operating in a repetitive manner over a finite time interval, which may be denoted as $[0, T]$. Since then, a mature framework has been built up for the development and analysis of linear ILC. The Figure 8 illustrates the general block diagram of an iterative learning scheme. Here k is the trial number and the object is an updated input u_k such that $\lim\limits_{k\to\infty} e_k = 0$.

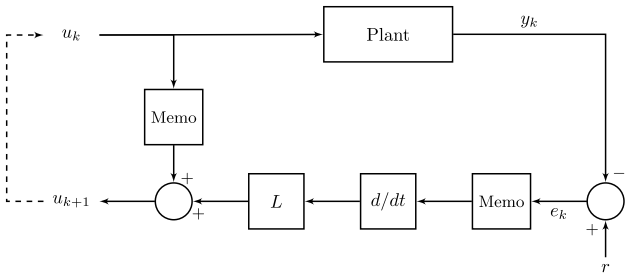


FIGURE 8. General block diagram of D-type-ILC based controller [135].

In [131] a basic ILC form was applied to a quadrotor to obtain increased performance through learning. The emphasis was on performing some fundamental missions for a quadrotor through simulations for different missions. In order to control the quadrotor, three different methods were applied: off-line ILC, on-line ILC, and a combination of both on-line and off-line ILC. These have the respective forms

$$u_{k+1}(t) = \underbrace{u_k(t) + K_P e_k(t)}_{\text{offline P-type}}, \tag{2}$$

$$u_{k+1}(t) = \underbrace{u_k(t) + K_P e_{k+1}(t)}_{\text{online P-type}}, \tag{3}$$

The authors designed an on-line ILC update for quadrotor trajectory tracking control, employing an inner proportional-derivative (PD) controller in order to stabilize the system given by

$$u_{k+1}(t)=u_k(t)+k_p e_k(t+1)+k_d\left[e_k(t+1)-e_k(t)\right] \qquad (4)$$

where t indicates the sample number in discrete time. The system showed large tracking errors but ILC was able to reduce it in subsequent iterations.

Another study was conducted in [132] and implemented the same basic ILC of [131] with an adaptive component to enhance the controller performance and robustness. This was applied to a quadrotor and experimental results showed good tracking performance in the presence of disturbances. However, both [131], [132] used the basic PD-type ILC form and could not ensure monotonic convergence, which means that the average error may increase throughout iterations as k increases.

Similarly to [131] and [132], the authors in [133] also developed a PID controller based on basic ILC form to optimize the travel path; this provides a controllable flight in various environmental conditions, especially after changing the total mass of the UAV (by adding extra load). The difference is that the parameters were tuning manually and no practical experiment has been done in [131] and [132], while real-time auto-tuning method for parameters based on the basic ILC form was considered in [133]. The next group of references will focus on ILC in combination with different control approaches.

The above basic ILC strategies were all based on the assumption that the ILC requires a tuning gain matrix and in one case a delay-time constant, and do not require an explicit model. This simplicity aids usability but necessarily degrades performance. Thus in [134], [135] and [136], optimization based ILC approaches are used to address these limitations. In [134] and [135], the performance of ILC in gradient-based that enhances a quadrotor's controllability and stability during attitude control is examined. Again in [136], the optimization based ILC approach was applied to achieve quadrotor trajectory tracking while balancing an inverted pendulum. Figure 9 presents the image sequence of application of ILC to a quadrotor by tracking a small trajectory indoors and the convergence of ILC when applied to a quadrotor.

The experiments in [134], [135] and [136] showed the fast rate of convergence of the norm error which is low after a small number of trials, although in some cases the method is slow as illustrated in Figures 10 and 11. It was shown that both studies outperformed the strategy proposed in [130]–[132] in terms of convergence speed, trajectory tracking performance and robustness. One shortcoming of this strategy is that it neglects the impact of non-repetitive noise on the system output.

Other attempts to address the disturbance using the ILC in combination with different control approaches have been conducted in [137], [138]. In [139], the authors designed a Back-stepping Integral Sliding Mode Control (BISMC) with ILC algorithm for a quadrotor. The back-stepping is responsible for tracking the desired trajectory, then the integral sliding mode controller is designed and analyzed for coping with the uncertainties and external disturbances. Finally, iterative learning control is designed to improve the accuracy of the tracking. Meanwhile [138] introduced a design based on the capabilities of $\mathcal{L}_1$ adaptive control combined with ILC to achieve high-precision trajectory tracking in the presence of unknown and changing disturbances.

The two approaches [137], [138] are similar in terms of using the same basic ILC; the addition of which improves the accuracy. However, the constraint described in [138], that the backstepping relies heavily on the dynamics of the system, that the system is not given in strict feedback form for both the attitude angles, and the integral sliding mode controller has chattering phenomena all limit its application. Moreover, the main challenge facing the approach in [138] is the training of the UAV to operate in changing environments, which is both complex and time-consuming in terms of both design life cycle and computational intensity.

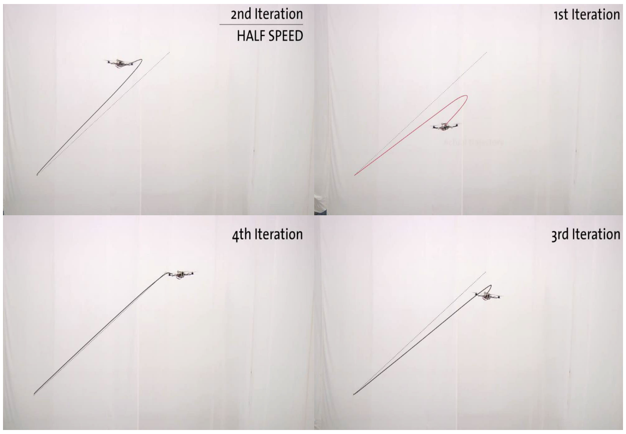


FIGURE 9. 1^{st} iteration to 4^{th} Iteration of ILC based trajectory tracking.

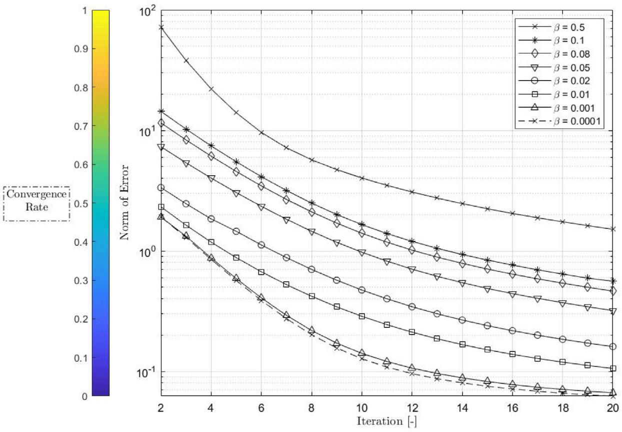


FIGURE 10. Optimized error convergence rate with a variation on the learning gain β values [135].

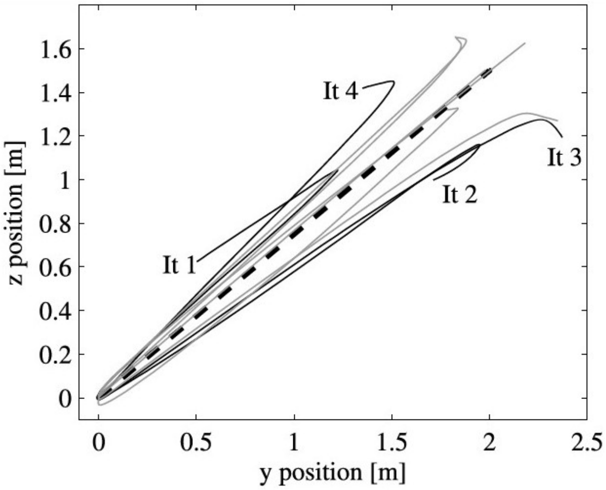


FIGURE 11. The diagonal trajectory experiment for quadrotor position in the *yz*-plane starting from the 1^{st} until the 10^{th} iteration [136].

Finally, in Tables 4 and 5, we summarize some of the recently developed ILC algorithms in equations applied to UAVs and the strategies of ILC for more generalized and specific tasks, respectively. It is shown from Table 5 that for a large class of practical systems, such as autonomous aerial refueling based on terminal ILC [142], [143], it is required that the output achieves perfect tracking at more than one defined time instants $t = t_i$ respectively. Therefore, it needs an extension of terminal ILC to solve problems which only require tracking of a number of critical positions for a subset of time instants.

TABLE 4. ILC algorithms in equations applied to UAVs in recent works.

Algorithms	Equations	Ref.
P-type	$\mathbf{u}_{k+1}(t) = \mathbf{u}_k(t) + \gamma e_k(t)$	[131], [132]
D-type	$\mathbf{u}_{k+1}(t) = \mathbf{u}_k(t) + \alpha \dot{e}_k(t)$	[131], [141]
PID-type	$\mathbf{u}_{k+1}(t) = \mathbf{u}_k(t) + \gamma e_k(t) + \alpha \dot{e}_k(t) + \beta \int_0^t e_k(s)ds$	[132], [134], [140], [143]
Adjoint-type	$\mathbf{u}_{k+1}(t) = \mathbf{u}_k(t) - \alpha \eta_k(t)$	[140], [141]
Gradient-based	$\mathbf{u}_{k+1}(t) = \mathbf{u}_k(t) + \beta_k R^{-1} G^T Q \mathbf{e}_k(t)$	[134]
Norm Optimal	$\mathbf{u}_{k+1}(t) = \mathbf{u}_k(t) + G^*(I - GG^*)^{-1} \mathbf{e}_k(t)$	[135]

A range of ILC approaches have been reviewed, including simple structure controllers for ILC which have been presented in discrete-time. Also, the above methods are limited in terms of the accuracy they have attained. They also require a significant level of computation as well as initial identification procedures and tuning. The following points are noted (i); there is a clear scope to evaluate a wider range of ILC methods on quadrotors; (ii) the review has shown that UAVs for fault detection are hampered by a number of limitations that can only be addressed by more accurate motion control and the ability to perform automatic transition tasks; (iii) tracking pylons is an inherently repetitive task, which also combines precise actions (e.g., location of equipment) and more flexibility in maneuvers (e.g., moving between pylons and HV lines).

These attempts were used to motivate new ILC algorithms for applications to quadrotors. This will especially motivate the development with a novel design approach for ILC based on gradient type or norm optimal, enabling system constraints to be satisfied while simultaneously addressing the requirement for high-performance tracking. This promising application could show that a ILC design can be formulated, derived and tested on quadrotors. Finally, the following section will review the possibilities of exploiting electric recharging from the power lines in an autonomous manner and the difficulties involved.

V. AUTONOMOUS RECHARGING STRATEGIES IN UAV APPLICATIONS

From the previous review, the UAV-based inspection method will save energy, simplify access to HV lines, reduce inspection costs due to using accurate control approaches and less reliance on expensive sensors, and automate the inspection process. However, automation of the inspection process still cannot achieve full automation, and with compromised performance due to the battery capacity of a medium scale drone that limits their travel distance and mission duration. This section will examine the most feasible and reliable technique to charge UAV using power lines.

This leads us to the next question of prolonging UAV mission duration. There are two options available in this context; (i) to increase the battery capacity via state-of-the-art battery material technologies, and (ii) to charge the battery from an external source which can be either wired or wireless approaches. Our field of review will focus on the second option as wired charging is deemed impractical.

There are numerous techniques available in the literature and these can be classified as either (i) conventional cord charging [144] or (ii) non-conventional contactless charging [145]. Table 6 shows the ways various UAV charging options are classified. As shown in Figure 14, the subject of UAV charging in modern applications can be divided in the proposed flowchart. Given that the overhead power lines (OPL) are fairly common in both urban and rural areas, this provides the inspiration for scientific research by drawing upon them as a source to charge UAV batteries. As demonstrated in Figure 14, there are mainly two options which can be utilized in order to implement this technique, namely power line dynamic charging and wireless power transfer (WPT).

WPT is the technology that enables a process of transmitting electromagnetic energy from the source of energy to receiver via an air gap, without using any connecting cables between them [146]–[149]. This technology was presented in the beginning of the twentieth century by Nicola Tesla, and he obtained a patent for improved Hertz's wireless transmitter [150], Figure 12 shows the Wardenclyffe Tower proposed by Tesla to transfer electrical energy without cords.

TABLE 5. Summary of iterative learning control scheduling strategies.

Approaches	Applications	System Control	Objective	Constraint	Solution	Performance Evaluation	Ref.
Generalized ILC	Surveillance-based applications in UAVs	Region-to-Region ILC	To minimize the overall distance travelled, guaranteeing passage through region at the specific times	Average time, Location, Constant power source, One-dimensional scenario, Trade-off (Single lost outside defined region)	Apareto optimization	Numerical simulation	[139]
Traditional + Generalized ILC	Aerospace (UAVs)	Adjoint-type ILC	To obtain a planar model of a helicopter, to prove effective in nonlinear non-minimum phase system	Complex computation, Low convergence speed	Linearized input-state system using flat output	Numerical simulation	[140]
Traditional + Generalized ILC	Autonomous Aerial Refueling (AAR) probe-drogue	Derivative-type ILC, Adjoint-type ILC, ILC based on additive state decomposition	To overcome disadvantage of only feedback control, Designing a docking controller in probe-drogue refueling	Sensitivity to (noise and disturbance), Complex computation, Low convergence speed	Additive State Decomposition	Theoretical analysis, Simulation	[141]
Generalized ILC	Autonomous Aerial Refueling (AAR)	Terminal iterative learning control (TILC)	To compensate docking errors caused aerodynamic disturbances model probe aerial refueling	Only terminal positions	ILC initial value estimation method	Simulation	[142]
Generalized ILC	Autonomous Aerial Refueling (AAR)	Terminal iterative learning control (TILC)	To choose the docking control in autonomous aerial refueling, to extending the range and long-time flight	Single point to point movement	Time allocation, 4 docking attempts start at time 50 (fail), 100 (fail), 150 (succeed), and 200 (succeed) s.	Theoretical analysis, Simulation	[143]

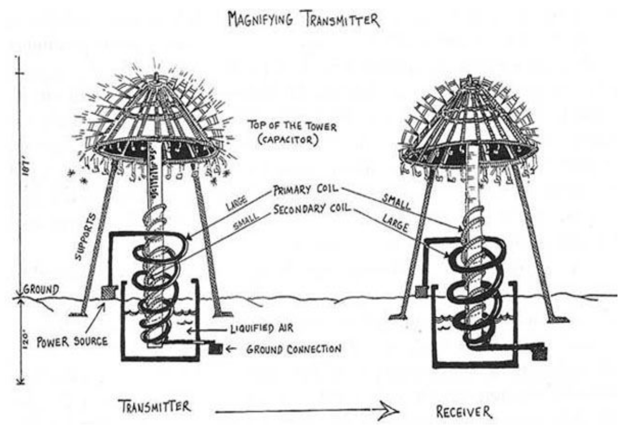


FIGURE 12. Schematic of the wireless power transfer via wardenclyffe tower.

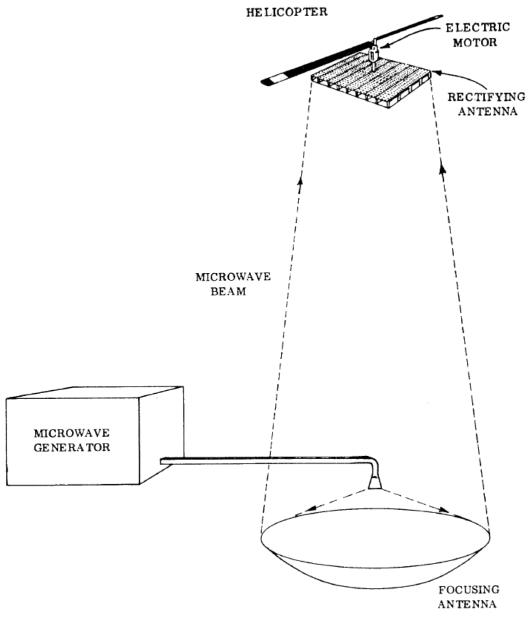


FIGURE 13. The basic elements of a microwave-powered UAV system [151].

In 1964, Brown made the first attempt to demonstrate the possibility of WPT for powering electric UAVs [151]. A small unmanned helicopter was able to pick up a maximum of 270 watts, when it was hovering 15 m above the ground based on a 2.45-GHz microwave beam as shown in Figure 13. Further attempts were made by WPT to enhance microwave powered airplanes in the 1980s and 1990s in Japan and Canada [152].

The WPT approach can be classified into two groups in terms of transmitting energy, namely (i) radiative [147], and (ii) non-radiative (inductive coupling and resonant inductive coupling) [147]. In the following subsections we present a brief overview of both radiative and non-radiative approaches with particular emphasis on available techniques that exploit the WPT approach by using OPL conductors to charge UAVs.

A. NON-RADIATIVE TECHNIQUES

The challenges of using existing WPT technologies for UAV charging include system efficiency, distance, the required power supply, transmission method, and human safety, all of which are reviewed for UAVs operating in a harsh environment. As illustrated in Figure 14, non-radiative charging can be classified into two techniques: inductive coupling [153], and magnetic resonance coupling [154]. The magnetic inductive and magnetic resonance couplings are very popular approaches for short and medium fields, where the generated electromagnetic field dominates the region close to the transmitter. In both techniques, the distance plays an important role in power transfer [155].

Accordingly, the range field power is attenuated according to the cube of the reciprocal of the charging distance [156].

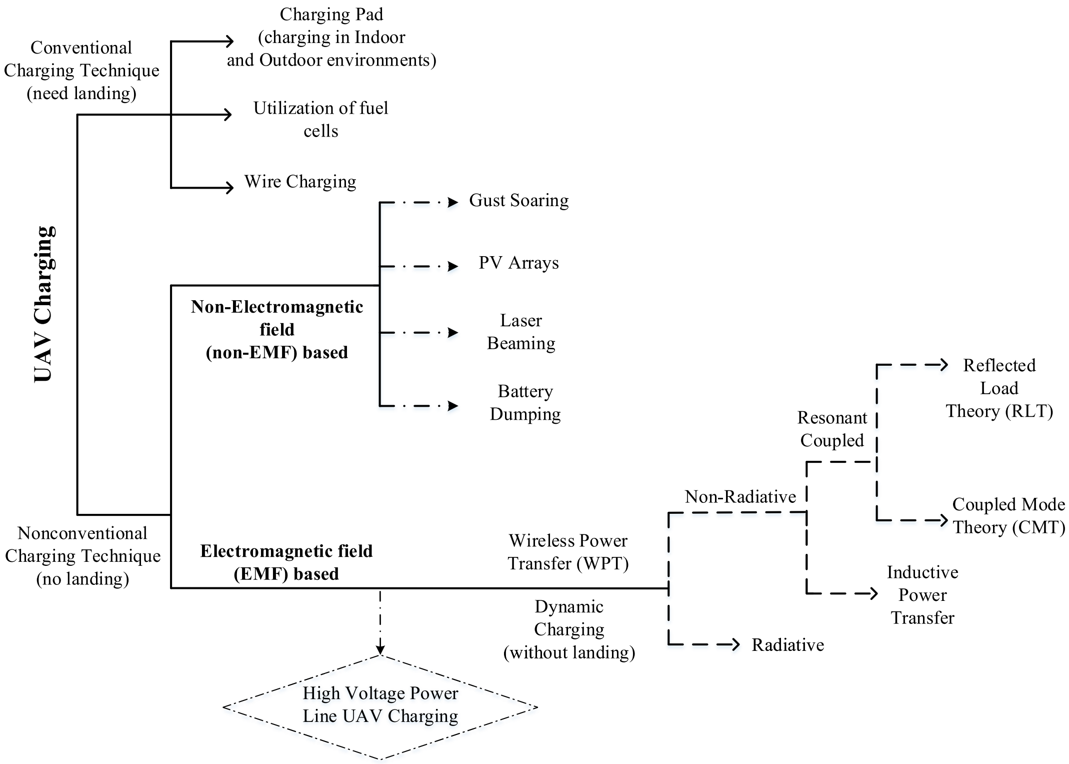


FIGURE 14. Classification of UAV charging technologies into conventional and non-conventional types.

In this subsection, we arrange the current applications of WPT (i.e., radiative, non-radiative) with regard to more relevant factor to the applications, that is the transmission distance, d, achievable for a desired power output.

1) VERY SHORT-FIELD APPLICATION ($d < 0.1$m)

Non-radiative technologies (inductive coupling and resonant coupling) that use WPT techniques for UAVs predominantly rely on the external sources of energy such as OPL conductors; these need to be operating at frequencies much higher than 50 or 60 Hz [157]. In general, the inductive coupling system consists of two main parts; the transmitter side and the receiver side. The transmitter side contains a power source, an oscillator, a power amplifier, and an inductor. At the receiving side, there is a receiving inductor, a rectifier, a voltage regulator or a limiter, and the battery of the UAV [158].

The authors in [159], propose a concept of wireless UAV charging using a self-sustaining PV charging station based on the resonant coupled WPT principles. The study concludes that a stable power transfer of 130 W over a distance of 50 mm can be achieved. Furthermore, the authors suggested to establish a network of such charging stations, that enhance the UAVs applicability to charging via WPT principles.

However, creating an infrastructure of charging pads for the UAVs still need more investigation to be imposed within strict design limitations in term of, costs, distances, electromagnetic shielding challenges, safety of systems operation.

2) SHORT-FIELD APPLICATION ($0.1\text{m} \leq d \leq 1\text{m}$)

The studies in [160] and [161], presented lightweight and energy-efficient solutions for non-radiative wireless power transfer for powering a UAV without a battery by design of a multi-MHz inductive power transfer system. The proposed solution includes the design of lightweight air-core coils that can achieve sufficient coupling without degrading the aerodynamics of the UAV, and the design of newly developed resonant power converters at both ends of the system.

The results show that by using the transmitting-coil that consists of a two-turn circular printed circuit board coil with an external diameter of 20 cm can obtain an average end-to-end efficiency of 60% was achieved for a coupling range of 23%-5.8%, where the range of motion drone was limited by 7.5 cm nylon string but can be extended to more than 20 cm. It should be noted that the specific absorption rate of human tissue for magnetic field is more than 1000 times lower than the permissible limit. Even though the concept has potential for implementation it still implies the complete disposal of the battery, may include an impractical solution in term of loss of contact, and interference from surrounding environments.

Again in [162], the UAV recharged the batteries of wireless sensors and other electronics from the electric grid. The

TABLE 6. Comparison of different wireless power transmission methods in UAV applications.

Techniques	Transferring Method	Frequency Range	Range	Efficiency	Payload	Control Flight	Battery Type	Safety	Ref.
Non Radiative	Inductive Coupling	10kHz-1MHz	Short	High	Medium	Manual	500mAh, LiPo	Yes	[160]
			Short	High	Light	Manual	Free battery	Yes	[161]
	Magnetic Resonant Coupling	10kHz-200MHz	Very Short	Medium	Medium	Manual	7000mAh, LiPo	Yes	[159]
			Short	Medium	Medium	Manual (PD controller)	2.1Ah, LiPo	Yes	[163]
Radiative	Laser	Up to ten of THz	Medium	Weak	Very Light	Semi-autonomy (Only lift-off)	Free battery	No	[164]
			Medium-field	Weak	Medium	Autonomous (Position control)	1350mAh, LiPo	No	[165]

difference from studies in [160] and [161], is that the system is based on a wireless magnetic resonant power transfer system that enables the UAV to transfer nearly 5 watts of power to a ground sensor. Moreover, the distance range between 0.2–0.3m for recharge with 4.43 watts in the first 30 seconds.

However, it is clear from the experimental results that there is a difference between transmission efficiency for both aerial scenario and static scenario that reduced overall power transfer in favour of the latter. This is due to many constraints, relative motion of the drive circuit and Tx coils on the UAV, deformations of these coils, and maintaining an exact position over the Rx coil.

B. RADIATIVE TECHNIQUES

The above-mentioned applications include the ability to charge from an external source, for example, an OPL connector. The following applications do not include this source for charging UAVs. However, they can be extended to work within the mid-range. Radiative techniques (i.e., laser power transfer) can be exploited for mid-range charging [163].

1) MEDIUM-FIELD APPLICATION ($1\text{m} \leq d \leq 5\text{m}$)

The authors in [164] demonstrated the possibility of powering insect scale aerial robots by radiating electromagnetic field based on the laser power transfer principle. The experiments showed a platform that was designed from a commercially available components and were used to achieve around 0.3 watts power output at 1m.

Similar to [164], the authors in [165] also developed a quadrotor platform with radiative (laser) power to optimize the travel path, aiming for an unlimited flight time. The power delivered was sufficient for a 1kg UAV to retain flight for 12 hours with rough estimates of power delivery of 100 watts. The difference is that the designing an insect scale UAV charging payload involves trade-offs among the power transfer range and weight against UAV flight stability in [164], while design to achieving robustness, and charging time at the expense of the payload for UAV in [165].

In Table 6, we summarize the comparison of different wireless power transmission methods in practical applications in term of range, transferring method, efficiency, payload of UAV, type of control, and safety of systems operation.

VI. CONCLUSION

In summary, this comprehensive review has shown that existing technologies for HV line monitoring have significant limitations. There is a clear need to reduce both significant costs that companies spend on monitoring HV transmission lines as well as the timescale involved in locating faults after they develop. The most critical need is to monitor and detect faults on the 11kV and 33kV networks operated by DNOs. Existing research focusses on signal analysis techniques which have limited accuracy. Little attention has been paid to harnessing recent advances in unmanned vehicles and surveillance. It is envisaged that this would have the advantages of a helicopter without the large operating cost and reduced potential hazard to the human operators.

Currently, the use of UAVs for fault detection is hampered by a number of limitations that can only be addressed by more accurate motion control and the ability to perform automatic transition tasks. Tracking pylons is an inherently repetitive task. It is also a task that combines precise actions (e.g., location of equipment) and more flexibility motions (e.g., moving between pylons and HV lines). This motivates the development of more general ILC-based algorithms for high-performance tracking with a view to improving accuracy from trial to trial by using information from previous executions of the task.

This review also describes the different leading approaches identified in UAVs in order to critically compare performance and inform design. Moreover, the review presents ILC algorithms to address the challenging quadrotor control problem. Specifically, these problems comprise difficulty in identification, nonlinearity and coupled MIMO dynamics. To address these, ILC is identified as an enabling technology for UAV control for OPL inspection as a promised control which can be expanded and generalised.

The various methods adopted in autonomous recharging strategies in UAVs applications by earlier researchers revealed that, finding a solution for prolonged mission duration is a complex task, particularly when charge the battery from an external source (OPL conductors). The fundamental conflict between accuracy, efficiency, reliability, and human safety is always present in these types of problems. A trade-off has to be made with these methods to arrive at the solution for autonomous recharging strategies that satisfy the constraints.

Generally, there are two issues to be considered in the design of recharging UAVs dispatch:

1) Given the fact that standard overhead power line frequencies utilized in the industry are 50 or 60 Hz, it is necessary to process a frequency conversion due to the operating range for method (i.e., magnetic resonant coupling) that lies in the kHz to MHz region.
2) Given that the frequency conversion process is necessary in WPT techniques, there are two options for designing the permissible weight of WPT conversion equipment; (i) overhead power line, and (ii) on-board the UAV. The former is limited in terms of the electromagnetic interference, shielding, and infrastructural maintenance. The latter instead is restricted by the UAV frame and payload.

Finally, as the world changes in light of the COVID-19 outbreak, it is also time for effective and proportionate change in these new circumstances. Moreover, integration of technological solutions such as UAVs in the power system will have a profound impact on mitigating the impact of COVID-19. Since it is a technology that does not depend on social communication and are restricted by the non-contact sensing technologies.

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The authors confirm that the data supporting the findings of this study are available within the article.

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