Overhead Conductor Condition Monitoring

Milestone Report 3

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THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

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Executive Summary

Energy Networks Association (ENA) member utilities have almost 800,000 kilometres of overhead conductor in service, valued at several billion dollars. Many of this critical infrastructure are ageing with some already reaching 70 years or replacement age. This project investigates the effective ways of condition monitoring of overhead conductor in Australian distribution networks. The objectives are:

- Review of conductor failure modes, degradation mechanisms and ageing parameters and current Australian industry practices to asset manage overhead conductors.
- Define the criteria for quantifying conductor condition and its end-of-life and determine the probability of conductor failure and estimate its remaining useful life.
- Identify the core areas of research and development for improving condition assessment of conductors in Australian Distribution Network Service Providers (DNSPs) networks.
- Survey state-of-the-art conductor condition monitoring techniques that could be used to monitor distribution conductor condition and assess the practicality and economics of applying these techniques in Australian networks.

This project was started on June 20, 2018. Having worked closely with project industry partners, the UQ team has successfully completed Milestone 1 and Milestone 2 tasks, including:

- A comprehensive review on the types, failures modes and geographical locations of conductors in Australian DNSPs' networks. The review was based on an extensive literature study on Energy Networks Association (ENA) 2015-2016 conductor survey, individual utility surveys, open source databases, IEEE, IEC and CIGRE standards and recommendations, and other literature as well as discussions with industry experts.
- A comprehensive study to understand the conductor degradation mechanisms and parameters that affect each type of conductor failure in Australian DNSPs' networks.
- Conducted a survey of the current Australian DNSPs' practice on conductor asset management and their requirements for a proactive yet cost-effective conductor condition monitoring, and identified core areas of research and development for an improved condition assessment of conductors on Australian DNSPs' overhead lines.

- Proposed and implemented a heath index methodology suitable for the bare overhead conductors in the Australian power distribution network. The methodology used a set of input parameters identified by analysing the Australian conductor failure statistics.
- The proposed health index methodology was trialled on a set of field data provided by the industry partners. The calculated health index values were in a good agreement with the industry experts' conductor health condition predictions.
- Proposed a mathematical model to provide the probability of conductor failures in Australian DNSPs' networks.

Milestone 1 and 2 reports were submitted to ENA on December 20, 2018 and August 20, 2019 respectively. Since the completion of the first two milestones, the UQ team has been conducting a survey of the state-of-the-art sensor based condition monitoring techniques, which could be applied to identify conductor defects and further enhance the health index methodology developed in Milestone 2.

The project team's progress since the 20th of August 2019 are summarised below:

- Reviewed existing overhead conductor fault identification and condition monitoring techniques to identify the most suitable method for the Australian DNSPs' networks.
- Identified that drone based visual inspections of bare overhead conductors whose health index has dropped below a pre-defined threshold level is the most suitable condition monitoring method for the Australian distribution networks.
- Identified image/video processing and machine learning techniques suitable for developing an automated image/video processing and fault detection platform for conductor visual data.
- Developed an automated platform for analysing drone captured visual inspections on bare overhead conductors.
- Trialled the developed visual inspection results analysis platform on an aged copper conductor.

Several Australian DNSPs are currently using IND technology's Early Fault Detection (EFD) technology on their networks. However, the project team has concluded that the EFD technology is more suitable for fault detection and prediction (in short term) rather than long term continuous condition assessment of distribution conductors. Thus, the main focus of

Millstone 3 was on the feasibility of drone based advance visual inspections for condition monitoring of bare overhead conductors in the Australian power distribution network.

The UQ team and industry partners have also been working on a plan for the successful implementation of the project into distribution utility businesses.

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1 Introduction

ENA members have almost 800,000 circuit kilometres of overhead conductor in service across Australia [1]. This represents an asset, which is conservatively valued over several billion dollars. Overhead conductor asset can be of different metal types, different sizes and capacities, and is employed in a range of climatic zones including tropical, temperate, arid, and highlands. Many conductor assets are ageing with some already reaching 70 years. Though many advancements in technology have been introduced on network assets throughout the years, approaches to cost-effectively monitor condition of conductors have not substantially changed. Existing conductor condition monitoring practices still rely on visual inspections and conductor replacement is usually driven by the frequency of conductor failures [2, 3]. Reliable and cost-effective methods to assess the likelihood of conductor failure have not yet been developed for the Australian distribution network service providers (DNSP) networks.

On June 20th 2018, ENA approved a research project proposal submitted by the University of Queensland team. The project is aimed at investigating how to effectively monitor and assess the condition of overhead conductor and to deliver an improved asset management strategy for conductors in Australian distribution networks. The objectives and deliverables of this project are as follows:

Milestone 1:

- A comprehensive report covering:
  1. Australian DNSPs experiences with conductor failure modes with the relevant information (conductor type, installation, operation, and maintenance, and failure location);
  2. Methodologies for defining the criteria for quantifying conductors' condition and its estimated end-of-life, and subsequently determining the probability of conductor failure and estimating its remaining useful life; and
  3. Possible areas of research and development for an improved conductor condition monitoring and asset management in Australian DNSPs' networks.

Milestone 2:

- A report on the development of a methodology and trial of a health index (HI) for assessing conductor condition.
- The results of the demonstration of the health index method in quantifying the condition of a representative type of distribution conductor

Milestone 3:

- A survey report on state-of-the-art conductor condition monitoring techniques (e.g. smart sensor and other advanced overseas techniques) for monitoring distribution conductor condition without having to de-energise the distribution network.

Milestone 1 and 2 reports were submitted to ENA on December 20, 2018 and August 20, 2019 respectively. Having been working closely with project industry partners and industry experts, the UQ team has completed the tasks required for Milestone 3. This report presents the outcomes of completing the original tasks of Milestone 3 as well as two additional tasks, being (1) investigating the use of a drone based advanced visual inspection methodology for conductor condition monitoring and (2) developing an automated platform for analysing the drone based images/videos of the overhead conductors.

Before, proposing drone based visual inspection technique, the UQ team has reviewed a number of existing condition monitoring techniques and fault detection methods, which has been developed for overhead conductors in the electricity networks.

Electricity companies around the world are trialling condition assessment and fault detection techniques for early identification of overhead conductor defects. IND Technology's Early Fault Detection (EFD) and LORD Technology's Distribution Fault Anticipation (DFA), Hydro-Québec's LineCore technology and self-navigating robots and drone based advanced visual inspections are some of the popular conductor fault detection / condition monitoring technologies [4-6]. The EFD and DFA fault detection schemes can be applied to distribution networks, however, the other conductor assessment methods have primarily been developed for the conductors in transmission networks.

Drones are becoming more and more popular in many fields such as agriculture, security and surveillance, military and engineering, particularly because present day drones are equipped with advanced camera technologies.

One of the additional tasks undertaken by the project team was a feasibility study and trial on the applicability of drone based visual inspections for condition assessment of bare overhead conductors in the Australian DNSPs' networks. The trial was conducted at the University of Queensland. Results of the trial revealed that drone based visual inspections is one of the best emerging technologies that can be used to improve the accuracy of condition monitoring of distribution conductor asset.

The inspection images/videos from the trial were then used to develop an automated methodology for analysing drone captured conductor visual inspection data with the aim to identify defective line elements efficiently. Findings of the project are presented in the rest of the report.

The remainder of this report is organized as follows:

Part 2 is a review on existing overhead conductor fault detection and condition monitoring techniques. Fundamental technical details, limitations and capabilities of each technique are discussed in this section.

In Part 3, drone based advanced visual inspection methodology is proposed for improving the accuracy of condition assessment of bare overhead conductors in the Australian DNSPs' networks.

In Part 4, project team's approach for effective deployment of drones for visual inspections of Australian distribution conductors is discussed.

The conclusions are presented in Part 5.

2 Review of Existing Conductor Fault Detection and Condition Assessment Techniques

The project team has identified a number of condition monitoring and fault detection techniques that are being used by DNSPs around the world for condition assessment and fault detection of distribution conductor assets. After a detailed review, the project team identified that IND Technology's EFD, LORD Technology's DFA, Hydro-Québec's LineCore technology and self-navigating robots and drone based advanced visual inspections are the technologies worth investigating. The aforementioned technologies are discussed below.

2.1 Conductor fault detection methods

2.1.1 IND Technology Early Fault Detection (EFD)

IND technology's EFD method is a continuous conductor monitoring solution [5]. It can remotely detect and locate radio frequency (RF) signals emitted by a faulty section of a line. The sensors used comprise of antennas and Rogowski coils placed every 5 km, which can detect micro arcs or Partial discharge (PD) signals. The data captured by the sensors are continuously uploaded to a cloud-based information management system. The collected data is analysed using machine learning algorithms in real-time.

Figure 1 illustrates the components of the EFD method.

The EFD technology is claimed to be able to detect deteriorating, damaged and broken overhead conductors, powerline vegetation encroachment and line contacts. The EDF technology has been trialled for a number of years in distribution networks in Australia.

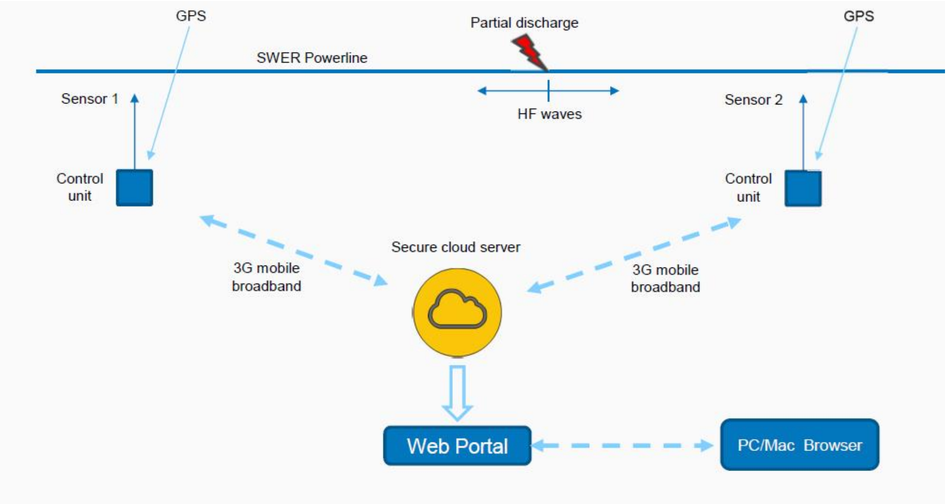

Figure 1 Illustration of IND technology's early fault detection (EFD) method for continuous conductor monitoring [5]

2.1.2 A Brief Review of LORD Technology's DFA Method

The LORD Technology's DFA method is also an online real-time condition monitoring technology [4]. It is intended to raise the asset managers awareness of the current system health condition and developing events. Unlike IND's EFD, the DFA uses Current Transformers (CTs) and Potential Transformers (PTs) to perform the measurements. The CT and PT waveforms are then sent to a software tool for classification, as illustrated in Figure 2.

This technology has only recently been installed in distribution networks in Australia, mainly to improve the reliability of overhead feeders.

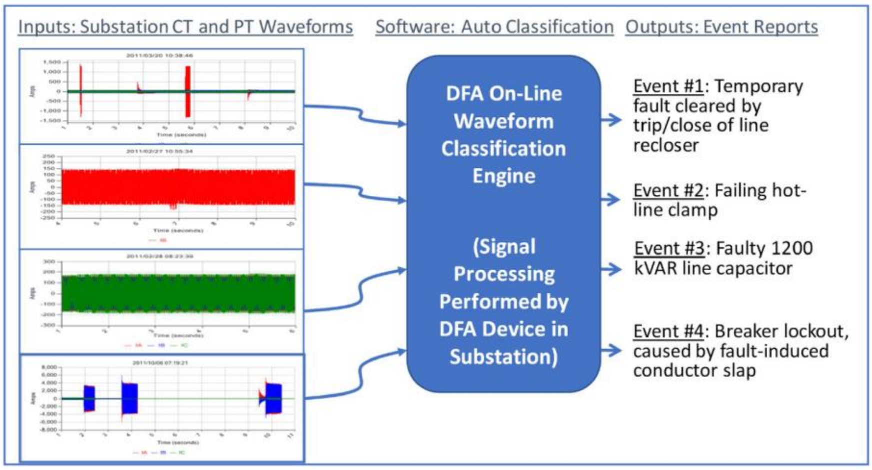

Figure 2 Illustration of LORD Technology's DFA method [4]

2.1.3 Self-Driving Robots by Hydro-Quebec's Research Institute (IREQ)

Hydro-Quebec's research institute (IREQ) has been developing and testing mobile robots for condition assessment of overhead conductors for a number of years. IREQ's robots are currently targeting overhead conductors in power transmission networks. However, the project team considered it worthwhile to study this technology and to understand its applicability to distribution networks.

The Hydro-Quebec's non-destructive transmission line testing mobile robots are primarily designed to detect the damages on Aluminium Conductor Steel Reinforced (ACSR) conductors. As illustrated in Figure 3, not all damages in ACSR conductors are visible on the outside layer of strands. Thus, Hydro-Quebec's technology has been designed as a platform which users can mount a range of sensors that can assess not only surface defects but also internal defects on ACSR conductors.

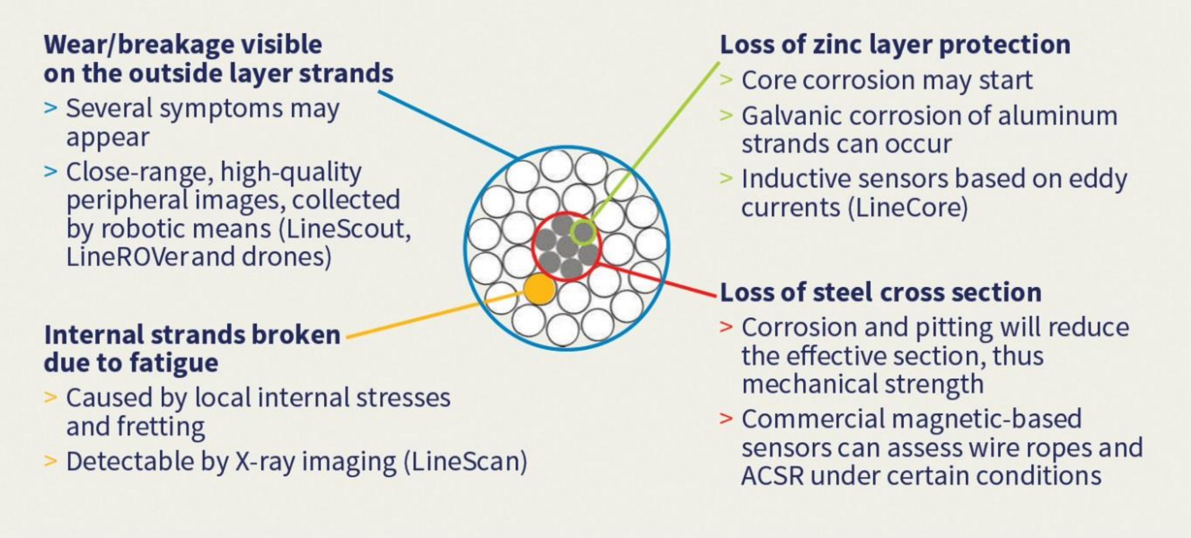

Figure 3 Signs of ACSR degradation and associated NDT sensors developed at IREQ [6]

LineROVer and LineScout are robotic platforms designed by IREQ to travel along the transmission lines preforming various non-destructive testings. These robots are lightweight, compact and remote controlled. LineROVer was originally developed for de-icing overhead ground wires and conductors. Later it was modified to travel along the energized transmission lines carrying various testing modules.

LineCore is an add-on module that can be mounted on LineROVer. LineCore enables non-destructive overhead line inspection of all types and sizes of ACSR conductors by determining the thickness and condition of the galvanic protection on the steel core.

LineScout is a remote-controlled robotic platform that can be used not only for line inspection but also for preforming maintenance tasks such as repairing broken conductor strands on conductors and ground wires. LineScout is capable of negotiating most of the line obstacles such as insulator strings, vibration dampers, warning markers and corona rings. Some of the applications of LineScout are visual inspections, verification of splice condition by measuring resistance, infrared imaging and detection of broken strands under suspension clamps using digital radiography. Bolt tightening and loosening, conductor strand repairing, vibration damper recovering are some of the maintenance tasks that LineScout is capable of performing.

Transmission conductors in Australia are primarily of the high strength ACSR type with long continuous spans. There are high costs to deploy the above methods and have only been sparingly used on transmission lines throughout the world.

2.1.4 Drone Based Visual Inspection of Distribution Overhead Conductors

Recent developments in drone technology have made drone based advanced visual inspections of overhead conductors a realistic alternative for conductor condition monitoring. Existing literature and industry experience have shown that drones can be utilised for effective visual inspection of overhead conductors and related assets.

One such commercial product is the LineDrone developed by IREQ. This is an octocopter (drone with eight propellers) specially designed for overhead line maintenance and inspection. One of its primary functions is to carry a LineCore platform and mount or dismount it from an overhead line. Another interesting feature of the LineDrone is its ability to land on a single conductor and travel along the line.

In 2007, a report was produced by EPRI reviewing technologies that can be used for inspecting overhead lines [7]. The report showed that twenty-four faults including conductor discolouration due to corrosion, broken or slack stay wires and traces of arching etc. can be detected and classified using optical or infrared cameras. Utah State University developed a similar technique named as Aerial Surveillance System for Overhead Power Line Inspection”[8].

Several works have been published on the application of image-based object detection in the electrical engineering related fields. In [9] Support Vector Machine (SVM) has been used as a classifier to extract information related to broken strands from a still image of an overhead line. In [10] an approach based on histograms analysis and neural networks is proposed for feature extraction and target classification to assess the condition of tower structures. In [11] a method which can recognize obstacles along a power lines such as insulator strings, counterweights and suspension clamps is proposed to enable a mobile robot to move along power lines. The segmentation of insulators out from images has been implemented in [12]. In another study, deep learning has also been applied to identify the faults in power lines monitoring by Unmanned Aerial Vehicle (UAV) [13].

A conclusion from the aforementioned works is for effective image based object detection there is a requirement for well-defined target features and large labelled training datasets.

3 Drone Based Advanced Visual Inspection of Distribution Overhead Conductors

As presented in Section 2, several existing overhead conductor condition monitoring techniques can be used for condition assessment and fault detection of distribution overhead lines. Among available techniques, some are fault detections methods (i.e. IND technology's EFD and LORD technology's DFA) while others are condition assessment methods. The EFD and DFA fault detection methods are suitable for monitoring distribution lines but have many disadvantages, such as:

- High cost to deploy
- Monitors only one or a small number of distribution feeders
- Large data analysis requirements

The IREQ suite of methods are more suitable for assessment of transmission lines, which are characterised by high strength conductors, primarily of the ACSR type.

The major disadvantage of the IREQ robot platforms are the weight of the robot platforms, which is around 23 kg. When other sensory devices are attached, the total weight will exceed 23 kg. Deploying such heavy equipment on an aged distribution conductor with unknown mechanical condition can significantly increase the risk of conductor damage or failure. In addition, distribution conductors have many different types of supports (pin, post, suspension and tension insulators) and connections. These add a large number of obstacles for the robots to navigate.

Considering the aforementioned issues, the project team concluded that an advanced drone based visual inspection methodology is the most appropriate condition assessment technique for bare overhead conductors in the Australian DNSPs' networks.

3.1 Objectives of Drone Based Advanced Visual Assessment

The objectives are as follows.

1. To identify the best method of capturing conductor surface visual inspections using drone mounted visual light cameras.
2. To develop a test platform which can automatically process drone captured images/videos and identify defective sections of overhead conductors.
3. To conduct a proof-of-concept drone based visual inspections of bare overhead conductor and use the visual inspection results to test the developed data processing platform.

3.2 Review of Drone Based Aerial Visual Inspection of Power System Assets

Drones have been utilised by DNSP's mainly for visual inspections of transmission and distribution overhead lines. The drones have also been used for draw wire stringing, chemical spraying and inspecting associated overhead electrical infrastructure (e.g. communication towers and easements).

If the drone is used for business purposes, there is a requirement in the Civil Aviation safety rules for a remote pilot licence (RePL) or a remotely piloted aircraft operator's certificate (ReOC). If the drone weight is < 2 kg, there is a "Sub 2 kg" category which can be utilised by such business as photographers, real estate agents and tradespersons.

The majority of the Drones used for overhead line inspections have a light payload (<2 kg) but the larger drones (> 2kg) can be used for carrying equipment for LIDAR inspections or chemical treatment of vegetation.

The non-technical challenges of flying drone are meeting the requirements of the civil aviation safety approval, particularly with keeping the drone within the visual line of sight and away from people and populous areas.

3.3 Australian DNSPs' Experience with Drone based Visual Inspections

Energy Queensland Limited (EQL)

EQL currently has over 100 of 'Remotely Piloted Aircraft - Drones' with 2 characteristic types; (1) with payloads < 2 kg and (2) with payloads > 2 kg, for a number of inspection and maintenance tasks. The company has around 230 registered pilots for flying the drones.

The smaller < 2 kg (drones) are used for the following tasks:

- Asset Inspection of Towers and associated equipment.

- Asset inspection of Pole mounted equipment.
- Asset inspection of Communication Towers and Communication Assets.
- General aerial photography (typically for work scoping).
- General aerial photography (Building /Property management).
- General aerial photography (Easement vegetation clearances).
- Adjacent equipment inspection prior to Live line activities (Trialling)
- Draw wire installation for aerial conductor stringing.

The larger > 2 kg (drones) are used for the following tasks:

- All the above plus
- Thermal imaging
- Cloud point capture from LiDAR
- Chemical spraying (Development almost complete)
- Line clearance with Flame thrower (still under development)

Drones allow EQL to rapidly investigate some parts of its network which are typically difficult to access in vehicles or on foot. Also, the high-resolution images captured by drones give EQL a better grasp of what damage has occurred and what equipment will be required to make repairs.

Aerial photography and other forms of drone-based data capture are conducted throughout Queensland as required. Analysis of drone captured data is currently performed manually. Drones are currently employed for routine communication tower inspection tasks, transmission tower and transmission asset inspections as part of the maintenance cycle. More opportunities for maintenance cycle work is being explored.

3.4 Proposed Methodology

The primary objective of deploying drones for visual inspection of bare overhead conductors in distribution networks is to capture detailed visual information from the surface of the conductors. Such data can then be processed to extract useful information to assess the health of the conductor.

Conductor surface visual information can be captured using several different drone mounted sensory technologies. Some examples are visible-light cameras, infrared cameras and corona

(UV) cameras. Infrared cameras are useful to detect defects that generate hot spots with elevated temperature levels i.e. aged joints and splices with higher contact resistance. Corona cameras are useful for detecting overhead conductor defects such as broken strands which, generate corona discharges. However, visible light cameras are the most common and widely available camera type. Recent developments in both drone and camera technologies have enabled the development of compact and easily controllable drones with very high-resolution cameras. Therefore, in this project, the focus is on the usability of visible light cameras to collect conductor surface visual information that can be used to estimate its health condition.

a) Data capture - camera specifications, methods and techniques

In general, even the recreational grade drones are equipped with cameras which are capable of capturing high resolution still images and videos. For example, consider the technical specifications of the DJI MAVIC AIR, an entry level drone (which costs less than AUD 1000) given in Table 1.

Table 1 Technical specifications of camera system of a DJI MAVIC AIR drone

Camera		
Sensor	1/2.3” CMOS Effective Pixels: 12 MP	
Lens	FOV: 85° 35 mm Format Equivalent: 24 mm Aperture: f/2.8 Shooting Range: 0.5 m to ∞	
ISO Range	Video: 100 - 3200 (auto) 100 - 3200 (manual)	Photo: 100 - 1600 (auto) 100 - 3200 (manual)
Sutter Speed	Electronic Shutter: 8 - 1/8000s	
Still image Size	4:3: 4056×3040 16:9: 4056×2280	
Video Resolution	4K Ultra HD: 3840×2160 24/25/30p 2.7K: 2720×1530 24/25/30/48/50/60p FHD: 1920×1080 24/25/30/48/50/60/120p HD: 1280×720 24/25/30/48/50/60/120p	
Photo Format	JPEG/DNG (RAW)	
Video Format	MP4/MOV (H.264/MPEG-4 AVC）	
Gimbal		
Mechanical Range	Tilt: -100° to 22° Roll: -30° to 30° Pan: -12° to 12°	
Controllable Range	Tilt:-90° to +17°	

Stabilization	3-axis (tilt, roll, pan)
Max Control Speed (tilt)	120°/s
Angular Vibration Range	±0.005°

According to Table 1, it is evident that the camera technologies are very advanced. The camera can capture images or videos of objects in a close proximity as 0.5 m. Further, fast automatic focusing technologies and sensitive 3 – axis gimbals are capable of capturing clear images and steady video clips. The camera sensor in the considered entry level drone is 1/2.3" image sensor with an image resolution of 12 Megapixels. Further, still images can be recorded in both compressed and uncompressed file formats. Videos can be recorded up to 4K quality i.e. 3840×2160 30 frames per seconds.

According to [7], different spatial resolutions and colour levels are required to detect different defects in overhead conductors as listed in Table 2. However, every drone camera available today are capable of recording still images in JPEG format with 256 colour shades per channel. More advanced cameras are capable if recording 64,000 shades per channel. Thus, it is clear that current imaging technologies are capable of recording still images of conductor surface which contain information required for identifying conductor defects.

Table 2 Wire Inspection Camera Requirements [14]

Fault	**Cause**	**Colour levels**
Shield Wire	Lightning	2
Connector Splice	Workmanship, thermal cycling, age	
Phase Conductor	External strands broken	2
Phase Conductor	Corrosion of steel core	256
Shield Wire	Corrosion	256

In addition to still images, surface visual data of bare overhead conductors can be recorded as a video file. Some of the critical defects in overhead conductors can be very small in size. Thus, when capturing surface visual data, it is extremely important to cover a significant length of the overhead line. On the other hand, taking still photographs of an overhead line without missing possible critical line segments are challenging. Recording conductor data as a video file is an alternative way of recording conductor visual data. By recording conductor surface visual information as a video file, the whole overhead line can be easily monitored without losing useful information.

A video consists of a collection of frames. Each frame is a still picture, when a video is being payed each still image is displayed sequentially with a predefined frame rate. A video clip of a conductor can be recorded by flying a drone above an overhead conductor as illustrated in Figure 4. While conducting a drone inspection special attention should be paid to maintain a constant distance between drone's flying path and the conductor. A graphical illustration of a video file of a conductor surface recorded by flying a drone above the line is illustrated in Figure 5. As illustrated in Figure 5, each frame of the video file is a still image of a conductor section. As each frame covers a conductor section, surface area covered by each frame overlaps with the surface area covered by the consecutive frame as illustrated in Figure 5. Thus, when processing a drone captured footage of an overhead line to identify possible defects, it is unnecessary to process all the frames in the video file. A set of frames which covers the total conductor length can be extracted from the video file and each frame can be processed using image processing techniques. By doing so, both computational power and processing time can be optimized.

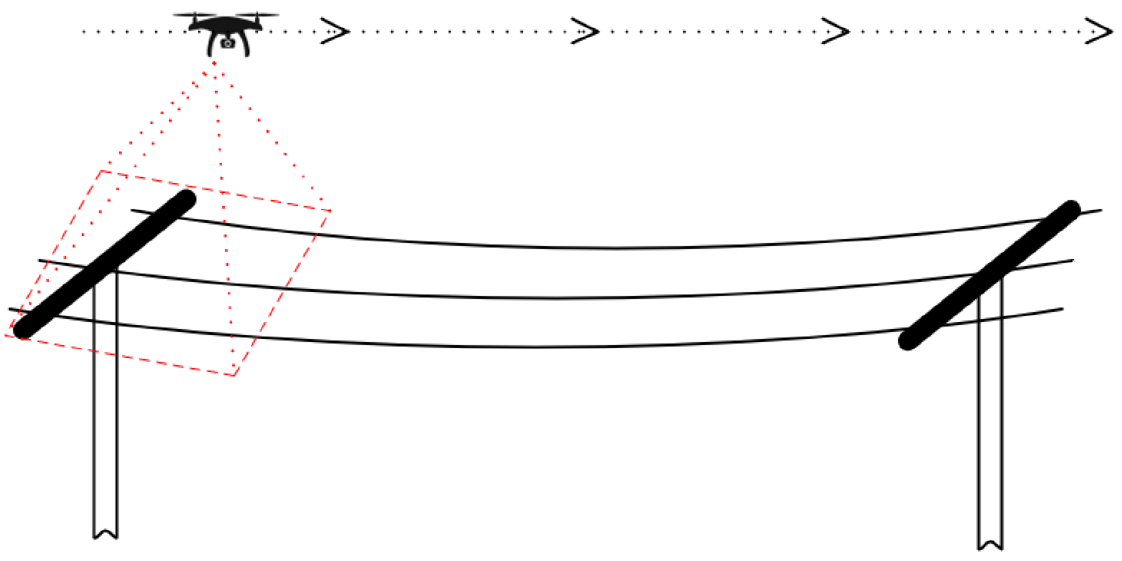

Figure 4 Flying a drone above an overhead line

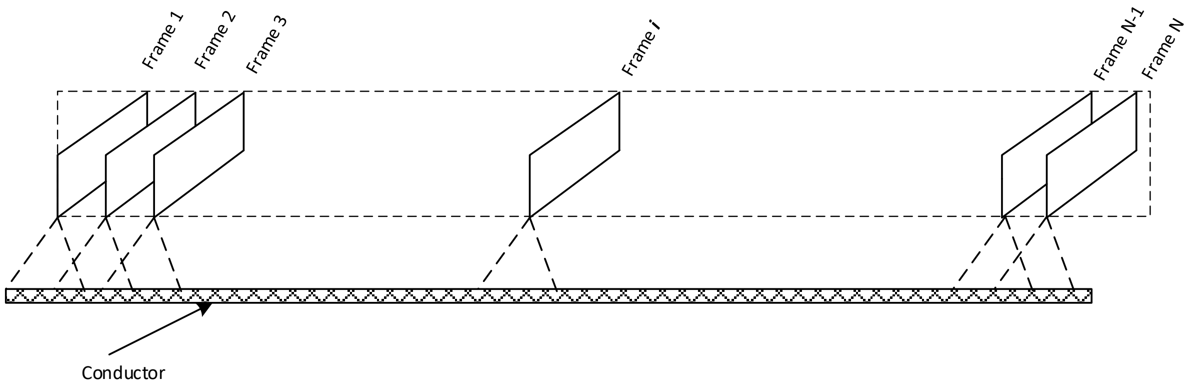

Figure 5 Graphical illustration of a video file of a conductor surface recorded by flying a drone above the line

b) Preliminary investigations on drone based visual inspections

A set of drone-based visual inspections of bare overhead conductors were conducted under controlled conditions for the purpose of determining the feasibility of using drones for surface visual inspections of bare overhead conductors. Test results were then used to trial image processing techniques and machine learning techniques which are suitable for developing an automated conductor defect identification platform.

Conductor surface visual inspections were conducted using the recreational grade, light weight (430 g) DJI Mavic Air drone shown in Figure 6. This specific drone model was used for proof-of-concept testing specifically because it is an entry level photography drone with basic imaging technology. There are many other drone models available which are equipped with more advanced imaging techniques than DJI Mavic Air drone.

Figure 6 DJI Mavic Air drone

Two trials were conducted in an outdoor location (see Figure 7) and a dedicated drone flying zone (Figure 8) at the University of Queensland. During both trials, an aged hard drawn 7/.064 (seven strands with each strand of 0.064 inches in diameter) copper conductor was used as the test object. The conductor was mounted about 3 m above the ground. As shown in Figure 7and Figure 8, the drone was flown directly above the copper conductor to capture surface visual information.

Figure 7 Conducting drone based visual inspections of a copper conductor in an outdoor location

Figure 8 Conducting drone based visual inspections of a copper conductor in a dedicated drone flying zone

The copper conductor used in this experiment had several defects including, an aged joint, loosened strands and loss of cross-section as illustrated in Figure 9, Figure 10 and Figure 11 respectively. Further, as can be seen in all three images, conductor surface has severe discolouration.

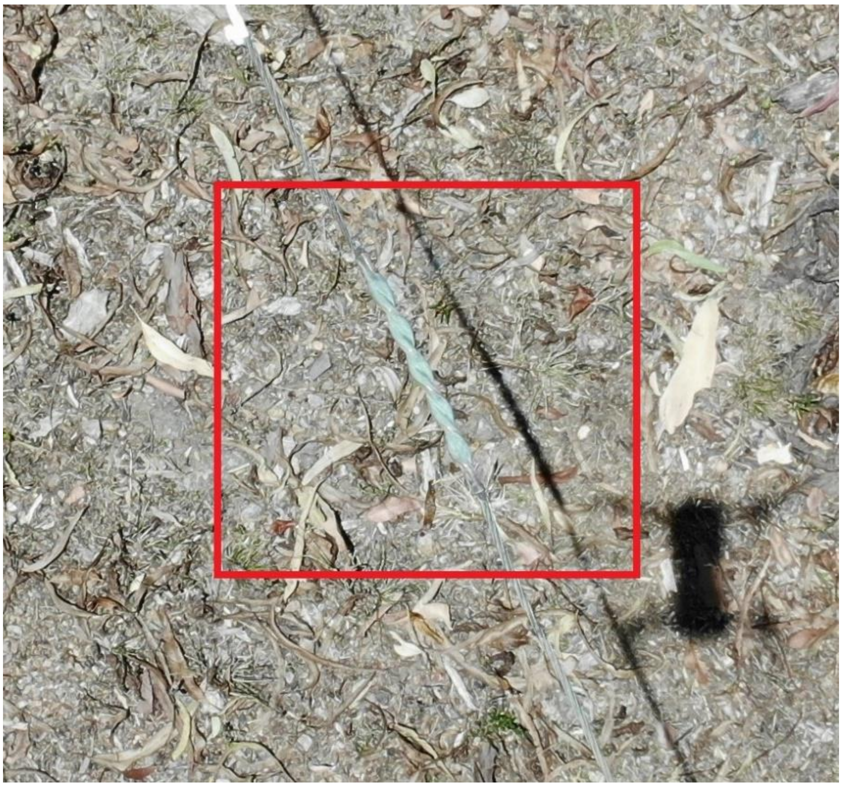

Figure 9 Aged joint in the test conductor

Figure 10 Loosened strands in the test conductor

Figure 11 Loss of cross section possibly due to arcing in the test conductor.

It should be noted that above images are frames extracted from videos recorded using a drone mounted camera. During the inspections the drone was flown approximately 1.5 m above the conductor. From Figure 9, Figure 10 and Figure 11, it is evident that the drone captured video footages of conductor surface contain information required to extract conductor defects on its surface.

To develop an automated machine learning based algorithm to detect surface defects, a large number of tagged images of each defect are required. However, such data are currently not available. Even though DNSPs have visual inspection data collected during routine inspections, tagging a large number of such data in not possible within the time frame of the current project. To overcome aforementioned challenges, in the conducted proof-of-concept tests, 2 cm wide markings were used to mimic three types of defects. The markings were made on the conductor surface using red, yellow and blue colour insulation tapes (see Figure 12).

Figure 12 Red and blue markings on the conductor surface

c) Proposed methodology for automated identification of conductor defects

This section of the report aims to present the image processing technique developed to automatically detect the artificially created surface defects (red, blue and yellow colour markings) on the conductor surface from drone captured video files. The method used is capable of fast and accurate image-based detection of pre-defined conductor defects in drone-captured videos.

Framework

Step 1:

Reading the drone-captured video: In this trial video files were recorded in .MP4 format at 30 fps (frame per second). Therefore, if the length of the video file is one minute, there will be 60 *30 = 1800 picture frames to be processed.

Step 2:

Process each frame sequentially: After the decomposition of the original video file into frames, each image frame is rescaled to a smaller size to guarantee the speed of fault detection meets the requirement.

Step 3:

Search for pre-defined defects in each frame by conducting a matching function. If the module finds an image segment similar to a pre-defined feature, the module will label the position of the defect. In the current work, colour and the location of artificially created defects will be marked.

Step 4:

Post processing of results: After completing steps 1 to 3, fault type and number of each fault along the inspected line segment can be extracted. The data can be used to generate a report for future reference and used for condition-based asset management of overhead conductors.

In the current work, a fault detection algorithm will generate a new video containing the detected defects, which is convenient for the asset managers to analyse the visual inspection test data.

Note: As mentioned before, red, blue and yellow colour marks were used as the conductor surface defects in the current work. Thus, matching algorithms were designed to identify the line segments with red, blue and yellow colour markings.

In reality this can be done using a machine learning based algorithm trained by using a labelled image database of the conductor.

The main steps involved in processing drone-captured video and fault identification are illustrated in the photos and flow chart shown in Figure 13.

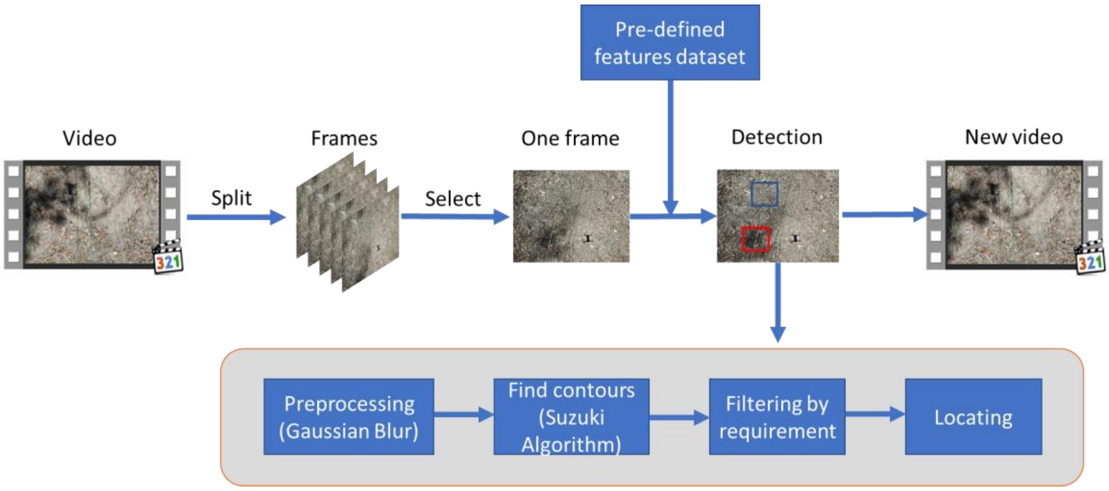

Figure 13 Main steps in processing drone-captured video and fault identification

Implementation

To implement the image processing and defect identification algorithm, Python programming language and OpenCV (Open Source Computer Vision) library was used. It should be noted that the proposed algorithm needs to be tuned for better accuracy. In another words, the features corresponding to different types of defects need to be adjusted during the training process to maximize the accuracy. However, if the features are designed too specific, the reporting rate will decrease. In contrast, if the features are defined too vague, there will be many incorrect reports during the detection process. Therefore, the project team suggests a trial and error approach which monitors both accuracy and speed of the algorithm to be adopted for tuning.

Results of the Preliminary investigations

A video file recorded during an outdoor trial was processed and analysed using the proposed algorithm. The algorithm was able to identify artificially created defects and mark them automatically on each frame as shown in Figure 14, Figure 16 and Figure 17. Further, the algorithm is capable of tracking an identified defect throughout the video until it disappears from the video (see Figure 15).

Figure 14 "Blue" defect automatically marked on a single frame by the proposed algorithm

Figure 15 Detected "Blue" defect is being traced continuously by the proposed algorithm

Figure 16 "Yellow" defect automatically marked on a single frame by the proposed algorithm

Figure 17 "Red" defect automatically marked on a single frame by the proposed algorithm

4 Effective Deployment of Drones for Condition Monitoring of Overhead Conductors

Performing drone based visual inspections for condition monitoring of overhead conductors during every routine inspection may not be practical. There are not only technical limitations such as lack of tagged data required to accurately train automated intelligent algorithms, but also practical limitations such as privacy issues and limitations imposed by aviation regulatory bodies, which may prevent frequent use of drones for visual inspections of overhead lines. Thus, it is important to identify the most efficient and practical method for deploying drones for visual inspections of overhead conductors.

4.1 When to deploy drones for Condition Monitoring of Overhead Conductors

It has been identified in Section 3.2, that drone based visual inspections have been deployed on overhead lines for certain maintenance tasks. It is suggested by the project team that the most effective use of the drones for condition monitoring of overhead conductors is to inspect when the conductors which are approaching end of life. This is the stage when there are likely to be a significant number of defects on the conductors to be identified.

Before deploying drones for the visual inspections, an estimation of its health index is recommended. The health index can be computed using the methodology proposed in the "Milestone 2" report of the current project. When calculating the health index, corrosion and annealing should be considering as the major degradation modes of distribution conductors in the Australian distribution network.

The end of life criteria for conductors has previously been suggested as the point where the loss of mechanical strength of the conductor is in the range of 10 % to 30%. There are 3 visual signs of end of life on conductors and these being one or more of the following:

1. Severe discolouration on copper conductors (green and black on copper)
2. Deep pit corrosion (greater than 30%) for all selected conductors (copper, aluminium and steel)
3. Broken strands

The flowchart presented in Figure 18 outlines the proposed overall condition monitor process for conductors. There are trigger points for the predicted end of life (based on Health Index) and end of life criteria (based on loss of mechanical strength).

It is proposed that to give an indication of end of life of conductors from both Corrosion and Annealing, the suggested steps for the Drone inspections are as follows:

1. Undertake Drone trial on conductors when the Health Index is below the threshold (in range of 0.4 to 0.5) - which is the predicted end of life for conductors
2. Take images of any significant defect on these conductors
3. Take images of any joint or connector on the line
4. Assess the degree of degradation, with the end of life defects being:
    a. Severe discolouration
    b. Deep pit corrosion (greater than 30%)
    c. Broken strands
5. Insert labels/tags on conductors which meet the levels of defects given in (4)
6. Determine if the defects are caused by localised events (e.g. lightning, conductor clashing, vegetation impact etc) and which the defects can be repaired
7. For the long-term defects count the number on a per feeder or per km basis – this can then be used for the strategic management of conductors

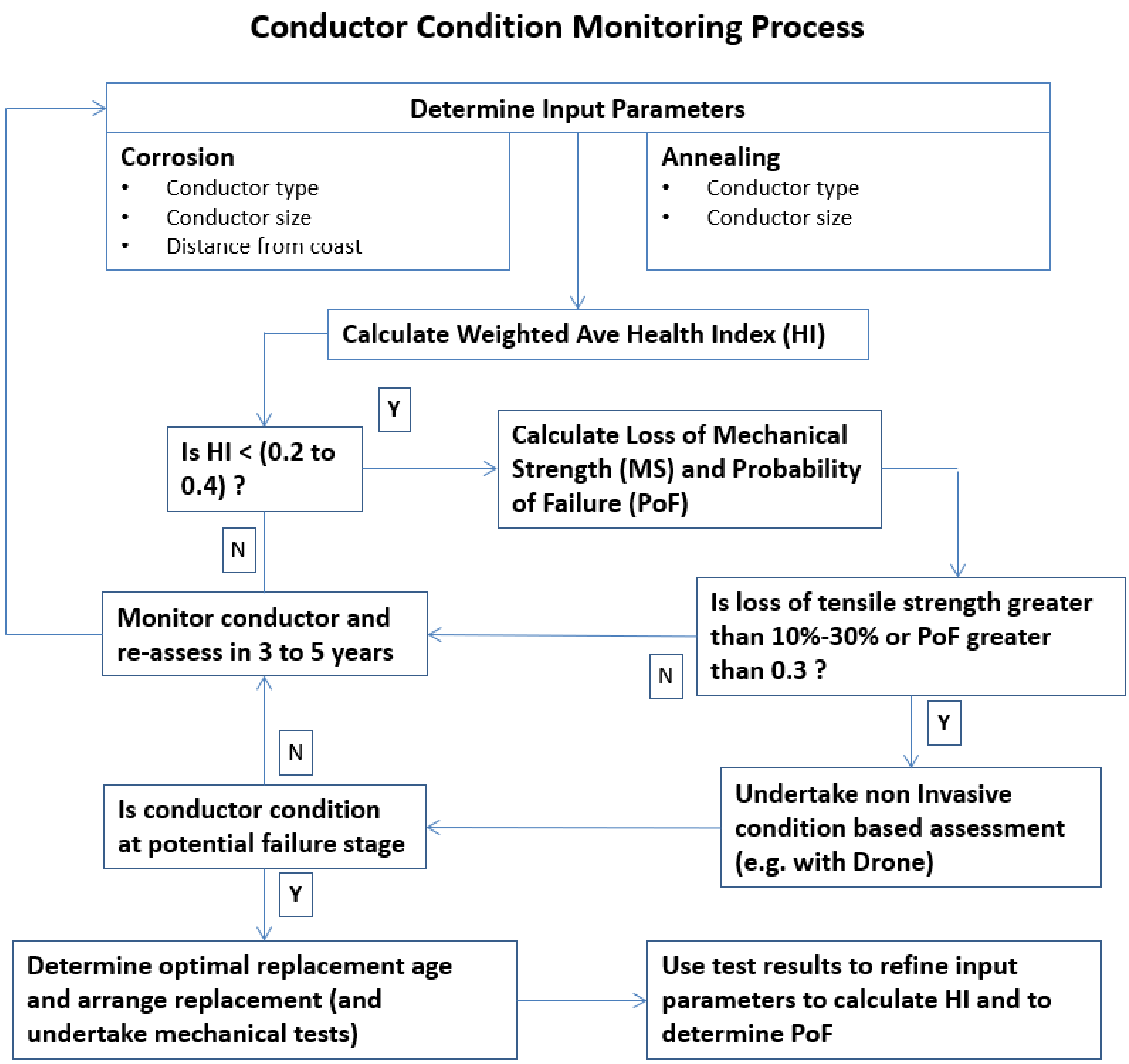

Figure 18 Proposed Condition Monitoring Process for Distribution Conductors

5 Engagement with Industry

The industry partners on the project team were from a small number of Australian electricity utilities. One of the latter requests from the project sponsors was for engagement with the entire electricity industry in Australia.

The project team gave a presentation on the project to around 34 industry participants at the API summer school in February 2020 and had intended to host a one-day face to face workshop for industry members by the end of March 2020.

Due to the COVID-19 and resourcing issues, there have been delays in finalising the project, and arranging the workshop. The restrictions now placed by the government means that a workshop cannot be held face to face. An online session for the workshop is being proposed in June 2020. The main aims of the workshop are (1) to discuss a number of case studies using the health index calculator and to refine or suggest revised parameters to be used in the calculation, and (2) to discuss how drones can be utilised effectively for condition monitoring of the distribution conductors.

6 Conclusions

6.1 Conclusions

This report presents the findings of a comprehensive survey on state-of-the-art conductor condition monitoring techniques that could be used to monitor distribution conductor condition and assess the practicality and economics of applying these techniques in Australian networks. Further, a drone based advance visual inspection methodology suitable for inspection of bare overhead conductors in the Australian distribution network is proposed.

The review of the existing state-of-the-art conductor condition monitoring techniques revealed that majority of the existing techniques have been developed for condition assessment of overhead conductors in power transmission networks, particularly the self-driving robots developed by the Hydro-Quebec's research institute. The fault detection methods of IND Technology Early Fault Detection (EFD) and LORD Technology's Distribution Fault Anticipation (DFA) may be suitable for distribution conductors, but they have significant drawbacks, such as the high cost for installation, the small number of feeders being monitored and the large amount of data analysis.

Among aforementioned techniques, the project team has identified that drone based advanced visual inspections as the most suitable method for condition assessment of overhead conductors in the Australian distribution networks. Preliminary investigations revealed that even an entry level recreational drone has the capability of capturing critical surface visual information of bare overhead conductors. An image processing based automated algorithm has been developed using Python programming language and OpenCV library for processing and classifying the overhead line defects. A methodology was developed and trialled using an aged copper conductor. The results of the field trial revealed the proposed method is capable of extracting conductor defects from still photographs and videos recorded using a drone mounted camera.

Finally, a suggested method of deploying drones for condition assessment of aged overhead conductors in the Australian distribution network was proposed.

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