ISPRS Journal of Photogrammetry and Remote Sensing 119 (2016) 10–31

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Review Article

Remote sensing methods for power line corridor surveys

Leena Matikainen [a,*], Matti Lehtomäki [a], Eero Ahokas [a], Juha Hyyppä [a], Mika Karjalainen [a], Anttoni Jaakkola [a], Antero Kukko [a], Tero Heinonen [b]

[a] Finnish Geospatial Research Institute FGI at the National Land Survey of Finland, Centre of Excellence in Laser Scanning Research, Geodeetinrinne 2, FI-02430 Masala, Finland
[b] Sharper Shape, 530 Lytton Avenue, 2nd Floor, 94301 Palo Alto, CA, USA

ARTICLE INFO

Article history:
Received 21 January 2016
Received in revised form 28 April 2016
Accepted 29 April 2016
Available online 26 May 2016

Keywords:
Power line
Review
Satellite/aerial image
Laser scanning
Lidar
UAV

ABSTRACT

To secure uninterrupted distribution of electricity, effective monitoring and maintenance of power lines are needed. This literature review article aims to give a wide overview of the possibilities provided by modern remote sensing sensors in power line corridor surveys and to discuss the potential and limitations of different approaches. Monitoring of both power line components and vegetation around them is included. Remotely sensed data sources discussed in the review include synthetic aperture radar (SAR) images, optical satellite and aerial images, thermal images, airborne laser scanner (ALS) data, land-based mobile mapping data, and unmanned aerial vehicle (UAV) data. The review shows that most previous studies have concentrated on the mapping and analysis of network components. In particular, automated extraction of power line conductors has achieved much attention, and promising results have been reported. For example, accuracy levels above 90% have been presented for the extraction of conductors from ALS data or aerial images. However, in many studies datasets have been small and numerical quality analyses have been omitted. Mapping of vegetation near power lines has been a less common research topic than mapping of the components, but several studies have also been carried out in this field, especially using optical aerial and satellite images. Based on the review we conclude that in future research more attention should be given to an integrated use of various data sources to benefit from the various techniques in an optimal way. Knowledge in related fields, such as vegetation monitoring from ALS, SAR and optical image data should be better exploited to develop useful monitoring approaches. Special attention should be given to rapidly developing remote sensing techniques such as UAVs and laser scanning from airborne and land-based platforms. To demonstrate and verify the capabilities of automated monitoring approaches, large tests in various environments and practical monitoring conditions are needed. These should include careful quality analyses and comparisons between different data sources, methods and individual algorithms.

1. Introduction

Electricity is vital for the activities of modern-day societies. To secure uninterrupted distribution of electricity, effective monitoring and maintenance of power lines are needed. The importance of the topic is increasing with the societies' increasing dependence on electricity, increasing occurrence of extreme weather conditions, such as storms, and tightening legislation and regulation in many countries (Pulkkinen, 2015).

Electrical networks typically include a nationwide transmission network, regional networks, and distribution networks. In forested countries, large parts of the networks are located inside forests. Monitoring of power lines basically includes two aspects: power line components and surrounding objects, especially vegetation. The condition of the components need regular checking to detect faults caused, for example, by corrosion and mechanical damage. Trees growing close to the power lines can damage the infrastructure and even cause large power failures or bush fires. Thus, there is also a need for regular inspections of vegetation inside and near the power line corridor to detect trees or tree branches that need to be cut. In addition, storms and other natural disasters can cause a great deal of damage to forests and power lines and a sudden need to detect the damage, often in difficult conditions. These general aspects of power line monitoring have been discussed, for example,

---

* Corresponding author.
E-mail addresses: leena.matikainen@nls.fi (L. Matikainen), matti.lehtomaki@nls.fi (M. Lehtomäki), eero.ahokas@nls.fi (E. Ahokas), juha.hyyppa@nls.fi (J. Hyyppä), mika.karjalainen@nls.fi (M. Karjalainen), anttoni.jaakkola@nls.fi (A. Jaakkola), antero.kukko@nls.fi (A. Kukko), tero.heinonen@sharpershape.com (T. Heinonen).

http://dx.doi.org/10.1016/j.isprsjprs.2016.04.011
0924-2716/

by Aggarwal et al. (2000) and Katrašnik et al. (2010) related to power line components and Ituen and Sohn (2010), Mills et al. (2010) and Ahmad et al. (2013) related to vegetation. Fig. 1 shows the main components of power lines and terminology used in the present article. Power line conductors between two adjacent pylons (i.e., over a span) have the shape of a catenary curve (see, for example, McLaughlin, 2006).

Traditional methods used for monitoring of overhead power lines include field surveys and airborne surveys. The core methodology has remained unchanged for decades. The inspections are conducted by teams travelling on foot or from helicopters, depending on, for example, how costs, different types of problems (e.g., faulty components or encroaching vegetation) and the certainty of detecting them are prioritised. The ground-based method is labour-intensive, but it allows for longer evaluation times and thus a higher problem detection rate. The helicopter method has a more limited detection rate due to the high speeds used and the limited ability of the crew to simultaneously observe all possible problem types. Both methods, however, depend on human visual observations. In addition to visual inspections, video recordings and various cameras can nowadays be used. Airborne laser scanning (ALS; also called lidar) has also become an important data acquisition approach. The first studies on this topic were done in the 1990s (e.g., Reed et al., 1996; Axelsson, 1999). The use of digital data from cameras and laser scanners has made it possible to separate data collection from data analysis. This is particularly important since data collection operations can then focus on minimising costs, and the digital data allow exact measurements, repeated analyses and long-term storage for comparison of data over time. The analysis of the data has, however, remained a manual process, and despite improved problem detection rates, significant cost savings have not been achieved.

Vast areas need to be covered in power line surveys, and remote sensing techniques thus provide interesting alternatives. In the past, various different remote sensing methods have been proposed and applied for power line monitoring tasks in research literature (see, for example, Mu et al., 2009; Li et al., 2012b). Applied data sources range from coarse satellite images to detailed photographs of the power line components. EPRI (2008) presented scenarios and technologies for future inspection of overhead transmission lines. A wide range of sensing technologies was discussed. Mirallès et al. (2014) presented a review of computer vision approaches applied to the management of power transmission lines as a conference paper. They discussed methods used for detection and inspection of power lines and insulators, power line corridor maintenance, and pylon detection. The review was not focused on specific platforms.

The objective of our review is to present the state-of-the-art of remote sensing-based surveying of overhead power lines and their surroundings in research literature. Compared to previous reviews, our study is more extensive. We aim to give a wide overview of the possibilities provided by modern remote sensing sensors from the application point of view and to discuss the potential and limitations of different approaches. Therefore, we consider all platforms: satellites, fixed-wing aircraft, helicopters, unmanned aerial vehicles (UAVs), and ground vehicles. Related studies using, for example, climbing robots and cameras mounted on poles are also briefly reviewed. Applications of interest basically include all power line monitoring tasks that can be carried out by using remotely sensed data. This covers both power line components and vegetation around the components, and both regular monitoring and monitoring due to disasters. To complete the discussion, some recent studies are included that are not specifically related to power lines but show the potential of new datasets for forest monitoring, detection of individual trees or detection of pole-like objects. Considering the development of effective power line monitoring approaches, knowledge of this research is important.

The paper is organised according to the type of remote sensing sensors used, beginning with coarse spatial resolution datasets and ending with the most detailed ones. For each type of data, some basic principles are first introduced, concentrating on aspects that are important for power line surveys. This allows us to discuss the

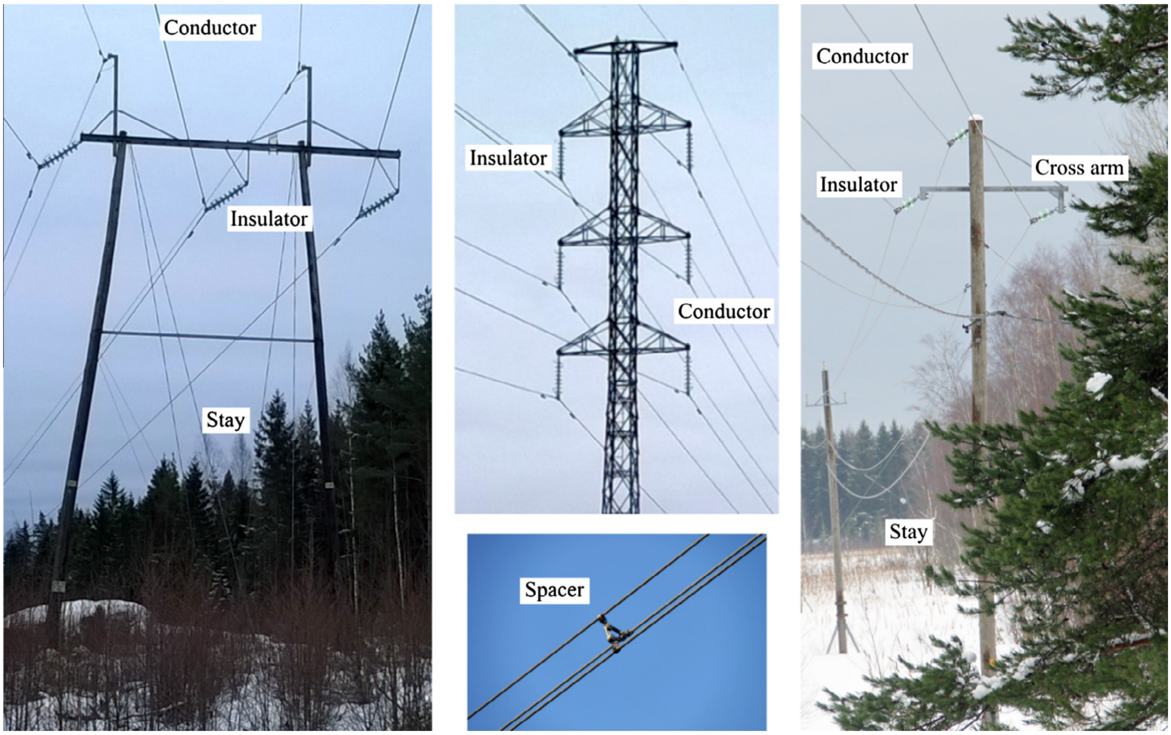

Fig. 1. Examples of transmission towers (left and middle), wood poles (right) and other power line components.

general potential and limitations of different approaches. Studies found in literature are then reviewed. In total more than 150 studies, mainly published in scientific journals and conference proceedings, are included. A large number of patents can also be found in the field of power line monitoring, but these were not included in the review. Following the overall objective presented above, our focus is on discussing various applications where the different data sources have been used. The main ideas of analysis methods and some representative quality analysis results are presented to understand the capabilities of various remote sensing methods. Due to the broad topic and large number of research articles, it was not possible to include all studies related to power line surveys or details of analysis methods. The discussion section summarises the results of the review. It concentrates on applications found in literature, specific advantages and challenges of the different data sources, and further research topics. Finally, conclusions are presented.

2. SAR images

2.1. Basic principles of SAR

Synthetic aperture radars (SAR) are active imaging sensors that operate in the microwave region of the electromagnetic spectrum (Henderson and Lewis, 1998). Wavelengths from approx. 3 cm to 25 cm (X, C, and L band) are typically used in remote sensing. A SAR system transmits microwave radiation, records backscattered signal from the target, and creates a 2D image-like presentation of the illuminated area. SAR images can be acquired using various platforms from small aircraft to satellites. Perhaps the most important benefit of SAR in Earth Observation (EO) satellites is that microwaves penetrate clouds, and SAR images can thus be obtained in all weather conditions, which makes them particularly interesting for applications such as disaster monitoring. Theoretically, SAR satellite images could be acquired from the same area even daily, but in reality the temporal resolution is decreasing due to technical limitations. For example, the Sentinel-1 SAR satellite of the European Space Agency (ESA) uses a pre-defined data acquisition plan and, as the operation time of the SAR is limited, it is not always possible to have images from the target area. On the other hand, by paying extra fees for priority data takes, SAR images can be acquired more frequently using commercial satellites. Very-high-resolution high-priority SAR images are relatively expensive, more than 100 euros/km^2. The theoretical highest spatial resolution available for satellite SAR images is better than one metre, but it should be noted that the spatial resolution of optical and SAR microwave systems cannot be directly compared. For example, SAR images appear to have a strong noise-like effect when visually observing the images. The effect is speckle, which causes pseudo-random variation of the observed radar intensities, and is an inherent feature of the coherent radiation used in SAR imaging.

In general, SAR image pixels include the following information: (1) radar backscattering intensity, (2) phase of the backscattered signal, and (3) range from the sensor to the target. The simplest approach to exploit SAR data is to use the intensity information, typically in the form of amplitude images, which can be easily visualised in many remote sensing software packages. The SAR backscattering intensity depends on many parameters, which therefore have a strong effect on the visual appearance of the image as well. These parameters can be divided into two categories: SAR system parameters and target parameters. Firstly, system parameters that have an impact on the intensity are the wavelength of the used microwaves, the signal polarisation, and the image acquisition geometry (SAR look angle from nadir and azimuth directions). In change detection applications, these parameters should be constant. Secondly, many target properties have an effect on the observed intensity, such as the surface roughness, surface moisture, vegetation biomass, and vegetation structure. The phase information is exploited in SAR polarimetry and SAR interferometry. Polarimetry is the field of SAR data processing dealing with the polarisation state of the transmitted and received microwave radiation (Henderson and Lewis, 1998). SAR polarimetry can be utilised, for example, in the classification of different objects and land-cover classes. SAR interferometry (InSAR) is a technique in which two SAR images acquired from slightly different perspectives, and having a geometric baseline (distance between satellites) of tens or hundreds of metres, are used, and the pixel-by-pixel phase differences between the images are converted into elevation differences of the terrain (Massonnet and Feigl, 1998; Rosen et al., 2000). An alternative way to extract elevation data from radar data is SAR radargrammetry, which is based on stereoscopic measurement of SAR images. Radargrammetry uses the intensity and range values of SAR data.

Even the highest resolution SAR images are rather coarse when considering the small features of power line components. Moreover, as SAR is a side-looking ranging imaging system, there are geometrical deformations and multi-path scattering, which make the analysis of SAR images very challenging in the case of complex targets such as power line structures. The backscattering behaviour of microwaves and the side-looking geometry of SAR sensors can sometimes bring out even small features, such as power line conductors, poles and towers. The visibility of the features, however, is dependent on their orientation compared to the imaging geometry. Power lines parallel to the azimuth (flying) direction are much easier to detect than those oriented in the range direction (Deng et al., 2012). Fig. 2 shows an example where part of a power line is clearly visible in a SAR image due to its favourable orientation. The side-looking geometry of SAR images is advantageous for detecting vertical features such as power transmission towers (Yan et al., 2011). Distortions related to the imaging geometry, especially layover and foreshortening, however, affect the appearance of towers in the imagery.

2.2. Mapping of power lines and towers from SAR data

2.2.1. Theoretical studies

Radar backscattering from power lines has been investigated in several studies related to collision avoidance of helicopters and aircraft (e.g., Sarabandi et al., 1994; Sarabandi and Park, 1999, 2000; Essen et al., 2002). These studies can provide theoretical background for developing power line monitoring algorithms, although it should be noted that the wavelength has often been shorter than in SAR images used for monitoring applications. For example, Sarabandi et al. (1994) performed polarimetric backscattering measurements for different types of power line conductors in the C, X and Ka bands. Sarabandi and Park (1999, 2000) tested power line detection based on the coherence between co- and cross-polarised backscatter components. Polarimetric W band or Ka band data were used. Sarabandi and Park (1999) also studied the effect of a water or ice layer on the scattering behaviour in the W band.

2.2.2. Studies based on airborne SAR data

Most SAR image -based studies found in literature have used airborne SAR data and concentrated on mapping of power lines and towers. It is typical of these studies that the authors have illustrated their results with a few figures, without larger tests and numerical quality analyses. We thus concentrate on summarising the main methodological ideas presented in the papers. Carande et al. (1998) showed that power line poles could be identified from height and coherence data derived from X band InSAR data. Woods

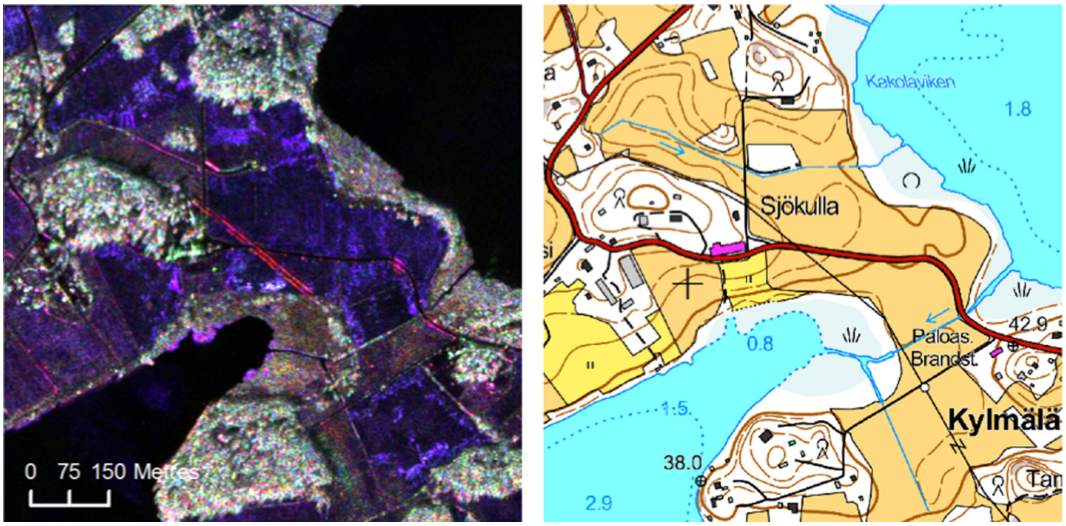

Fig. 2. Left: E-SAR airborne L-band SAR image. Original image data © DLR and Astrium GmbH 2000, image processing by the Finnish Geospatial Research Institute FGI. Right: Topographic map data © National Land Survey of Finland, 2015. Part of a power line can be seen on the SAR image as a red stripe in the middle of the image. The flight line was approximately parallel to the power line. The pixel size of the image is 1 m × 1 m.

et al. (2004) described a process for detecting vertical obstructions such as pylons and antenna towers from digital surface models (DSMs). DSMs discussed in the article were created from InSAR data, but the details of the SAR data were not given. The detection process was based on morphological filtering and criteria based on height, size and shape. Potential power line transmission paths were then detected by finding vertical obstructions that formed a line. Some height error analyses and discussion on the error sources were also presented.

Yang et al. (2007) presented a method for detecting power transmission towers from full polarimetric data. The method was based on polarimetric target decomposition and detection of point-like targets. The final transmission network was detected by connecting the detected points and analysing the lines obtained. L band airborne data were used in the study. Deng et al. (2012) also discussed the use of polarimetric data in the detection of power lines. Theoretical analyses were presented and a method based on the coherence between the co- and cross-polarisation was proposed. The method was tested by using simulated data and real P band data, and the results showed how the orientation of the line affects the detection results. Lin et al. (2012) presented experiments with airborne circular SAR imaging in the P band. A figure illustrated how power lines became clearly visible in the data acquired from a circular trajectory. Xie et al. (2014) discussed the use of parameters ‘linear polarisation ratio’ and ‘degree of linear polarisation’ in the detection of transmission towers from airborne L band data. In images based on these parameters, high-voltage transmission towers became clearly visible.

2.2.3. Studies based on satellite SAR data

Data from the latest high-resolution satellite SAR systems have been used in a few studies. Schwarz et al. (2009) discussed automated interpretation of high-resolution TerraSAR-X satellite images and illustrated with a figure how a power line pylon was visible in time–frequency decomposition results. Yan et al. (2012) studied the backscattering of transmission towers and lines in X band SAR images from TerraSAR and COSMO-Skymed satellites. This study also showed the dependence between the orientation of power lines and their visibility in SAR images. The scattering characteristics of different types of towers were illustrated with figures. Sha et al. (2014) used a time series of 20 TerraSAR images and studied the backscattering behaviour of a power line segment with six conductors. The authors found that changes in scattering positions were consistent with air temperature measurements and the changes could thus be related to the changing sag of the conductors.

2.2.4. Indirect monitoring of infrastructure using SAR interferometry

Satellite SAR data have also been used for indirect monitoring of the safety of infrastructure including power lines. Ge et al. (2007) applied differential SAR interferometry in mine subsidence monitoring. Various satellite SAR images were used. Iasio et al. (2012) discussed the monitoring of an Alpine landslide by using COSMO-SkyMed images and persistent scatterers interferometry (PSI). In both studies, the authors list power lines as one example of infrastructure that can come under threat. Luo et al. (2014) used TerraSAR images and the PSI technique for the monitoring of ground subsidence over a wide suburban area in China. Based on their analysis results, the authors also showed a figure illustrating the heights of power line supports.

2.3. Disaster monitoring around power lines using SAR data

A few examples can be found on the use of SAR data in the context of disaster monitoring around power lines. Zhang et al. (2010) described the use of an airborne SAR system for disaster monitoring after an earthquake in China. The system has an X band dual antenna interferometric sensor and a P band fully polarised sensor. The data were used together with optical satellite images, aerial photos and other geospatial data for the detection of different types of damage. Semi-automatic information extraction and visual interpretation were applied. Power lines and towers were mentioned among other objects of interest. Jingnan (2010) tested the scattering characteristics of an icing transmission tower and concluded that it is possible to monitor deformation changes in weather conditions promoting the build-up of ice using high-resolution SAR images. The study was described briefly. Details on the SAR images were not given. Yan et al. (2011) discussed the use of TerraSAR-X data to monitor power transmission towers in natural disaster conditions. The idea was to extract the height of towers from single images and to exploit this information to detect collapsed or distorted towers.

Ulander et al. (2005) studied the mapping of wind-thrown forests in southern Sweden by using Envisat and Radarsat satellite

SAR images and CARABAS airborne SAR images. A 5 km × 5 km test site with significant forest storm damage was used. In some parts of the area, 100% of trees had been damaged. The authors found that the storm-damaged areas could not be detected from the spaceborne images. This was due to their unfavourable frequency band (C) and coarse spatial resolution. Only a few damaged areas were visible in Radarsat fine beam images (spatial resolution approx. 9 m). According to the authors, L band satellite data are expected to improve the detection capability. From the CARABAS low frequency data (55 MHz; spatial resolution 3 m), most damaged and even partly damaged areas were detectable. Some power lines were also visible in the CARABAS data and in some areas they disappeared, indicating damage. Use of the CARABAS data for the detection of forest damages was also discussed by Fransson et al. (2002).

From other studies not related to power lines, it is known that modern satellite SAR images have potential for detecting storm damage in forests. This knowledge could be exploited in the development of disaster monitoring in power line corridors and their surroundings. For example, Eriksson et al. (2012) simulated storm damage by felling trees. They found that backscattering in TerraSAR X band data with HH polarisation increased and backscattering in ALOS PALSAR L band data with HH polarisation decreased when trees were felled. They also mentioned that images with fine spatial resolution showed shadowing effects that can help in the detection of damaged areas. Thiele et al. (2012) presented methods for forest border extraction and change detection from TerraSAR-X data. The purpose was to apply the methods for detecting wind-thrown areas and monitoring clean-up operations, respectively. It has also been shown that 3D SAR techniques, either stereoscopic measurements (radargrammetry) or InSAR, can be used to measure forest tree heights (Karjalainen et al., 2012; Solberg et al., 2013; Karila et al., 2015) if a digital terrain model (DTM) is available, and potentially to see forest storm damage if 3D data are available before and after the storm event.

3. Optical satellite images

3.1. Background on the use of optical satellite images

In this section, we consider the use of satellite images taken in the visible and near-infrared (NIR) spectral regions. These imaging sensors are passive, so they only receive energy reflected from the Earth's surface and cannot be obtained in darkness. Clouds, fog, and resulting shadows impact the satellite image quality and can prevent the use of the images. The resolution of the sensor can be described as the ground sample distance (GSD), that is, the distance between neighbouring pixel centres on the ground. It defines the smallest object size that can be recognised from the images. Sensors can be classified based on their GSD e.g. to low ($\geqslant$30 m), medium ($\geqslant$5 – < 30 m), high ($\geqslant$ 1 – < 5 m), and very high resolution (<1 m) sensors (Dowman et al., 2012). Current very high resolution satellites with GSD $\leqslant$ 1 m include, for example, IKONOS-2 (GSD 0.82 m), EROS B (0.7 m), KOMPSAT-2 (1.0 m), KOMPSAT-3 (0.7 m), Resurs-DK 1, WorldView-1 and -2 (0.46 m), GeoEye-1 (0.46 m), Cartosat-2 series (0.82 m), Pleiades 1 and 2 (0.5 m), and SkySat-1 and -2 (0.9 m). A limiting factor for the broad use of very-high-resolution satellite images in power line monitoring may be that the weather conditions, especially cloud cover, hinder image acquisition. It is not necessarily easy to obtain images from cloudy areas of the world in certain time periods. In addition, the use of very-high-resolution images may become costly, and several customers can be competing for the satellite's imaging resources at the same time.

Conductors or bundles of them are thin, even when considering satellite images with the highest resolution. For example, new 400 kV power lines in Finland have a triangle bundle structure (per phase) in which the length of one side of the triangle is 450 mm and each conductor has a diameter of 32 mm. 110 kV power lines can have a two conductor bundle structure (per phase) with a space of 300 mm and a diameter of 24 mm, correspondingly. The open, low vegetation corridors are usually 26–30 m wide for 110 kV and 36–42 m wide for 400 kV power lines in Finland. They are visible in the medium resolution satellite images. Fig. 3 shows two high voltage power line corridors in forested environment on a RapidEye optical satellite image. The GSD of the image is 8 m. The forest is mixed forest with coniferous and deciduous trees. The image was acquired in early spring when deciduous trees and grass were not yet green.

Due to the limited spatial resolution, power line inspection studies using optical satellite images have focused on analysing the environment of the conductors rather than the conductors themselves. In particular, vegetation monitoring has been the main topic in published studies. Height information, which is important in vegetation monitoring, can be derived from optical satellite images if stereo images are available (see also Section 4.1). For forest height measurements, a DTM is also needed.

From very high resolution satellite images it can be possible to detect both pylons and conductors (e.g., Moeller, 2006). In the study of Bernstein and Di Gesù (1999) one of the objectives was to find out if power line towers and lines were visible in one metre resolution images. The authors' object recognition system could then be used for fast electric power line damage detection after the storm. Object recognition of 3-, 2-, and 1-line structures were tested and the success rate was about 80% for towers and 75% for lines. Thus this resolution was useful.

3.2. Monitoring of vegetation in power line corridors using optical satellite images

Studies presented in the following have discussed corridor and near zone vegetation inspection and they have concentrated on presenting the methodology.

Ahmad et al. (2013) studied the vegetation encroachment onto transmission lines. The paper discussed a concept of utilising multispectral satellite stereo images to recover a 3D digital elevation model (DEM) of transmission lines rights-of-way to identify dangerous vegetation that can strike the power lines and cause blackouts. Ahmad et al. (2011) dealt with the same satellite stereo images theme. The vegetation monitoring method to detect potential interference presented in the article consists of three steps: merging multispectral and panchromatic images, vegetation detection using the normalised difference vegetation index (NDVI), and calculating the height of trees from satellite stereo image matching. The paper of Kobayashi et al. (2009) also introduced a concept for the use of multispectral stereo pairs of satellite images to identify dangerous trees and plants along overhead transmission rights-of-way. The safe distance from vegetation to transmission line depends on the voltage, and it is approx. 0.3 m (15 kV) – 7.3 m (500 kV). The location of healthy vegetation was calculated using the NDVI. The appropriate NDVI threshold value depends on the area. A stereo matching technique was used to calculate the height of vegetation. The paper of Moeller (2006) discussed a method based on the analysis of multispectral and stereoscopic very high resolution Quickbird satellite imagery. After preprocessing of the data and pan-sharpening, tall vegetation is extracted from the multispectral bands using texture and the NDVI, and vegetation height is then calculated from the stereo images. Finally vegetation with a potential interference with

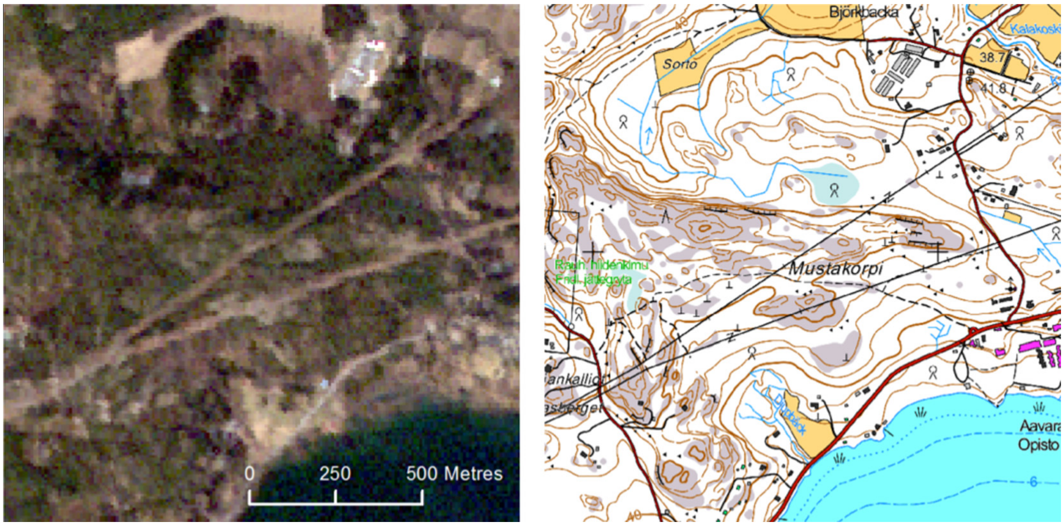

Fig. 3. Left: RapidEye optical satellite image. Includes material © (2013) BlackBridge, LLC. All rights reserved. Right: Topographic map data © National Land Survey of Finland, 2015. The figure shows high voltage power line corridors in forested environment. The pixel size of the satellite image is 8 m × 8 m.

power lines can be mapped. In Moeller (2006), only the vegetation mapping was realised.

Raggam et al. (2005) studied the height accuracy of vegetation height mapping using spaceborne IKONOS images as well as aerial UltraCam stereo images. A laser scanner DTM and a coarse DTM, generated from 1:50000 topographic maps, were used as reference ground models to calculate tree heights. Compared to field measurements, the average height differences for trees located in the midst of the forested area were 1.8 m for IKONOS and 0.4 m for UltraCam when the laser scanner derived DTM was used. In the case of the coarse ground reference model, mean tree height differences were 3.1 m for IKONOS and 1.2 m for UltraCam. This study gives an example of achievable accuracy values for identifying dangerous trees near power lines from satellite images, although this application was not mentioned by Raggam et al. (2005).

4. Optical aerial images

4.1. Background on the use of aerial images

In this section, we consider the use of aerial images collected with a manned helicopter or a fixed-wing aircraft mainly in the visible and near-infrared (NIR) wavelengths. The use of thermal (long-wavelength infrared) images will be addressed in Section 5, and the use of ultraviolet (UV) images will be shortly referred to in Section 9. In addition, data acquisition from UAV platforms will be discussed separately in Section 8.

Both helicopters and fixed-wing aircraft have been used in power line monitoring applications, helicopters typically for inspecting power line components and fixed-wing aircraft for vegetation monitoring. The benefit of helicopters is that they are able to fly closer to the power lines than fixed-wing aircraft and, therefore, they can image the objects in more detail. As will be discussed later in this section, even sub-centimetre GSD can be achieved from helicopters. Helicopters have also the ability to hover around objects of interest which enables more thorough imaging of the object. In addition, it is easy to map an area repeatedly if needed and to follow a route which has sharp turns, such as in power line corridors. Fixed-wing platforms, on the other hand, have a faster flying speed than helicopters and thus they can cover larger areas more efficiently (Li et al., 2012b). The typical GSD of high-resolution aerial images collected using fixed-wing platforms is 5–10 cm.

3D information is essential in power line monitoring, and stereo photogrammetry is thus an important technique for producing height data from the images. If images overlap, stereo matching can be utilised to infer the 3D coordinates of the objects (Sun et al., 2006; Mills et al., 2010). The matching is performed using a method of triangulation, in which the same object point is seen on two or more images (Sonka et al., 2008). The 3D position is the intersection point of two or several rays that travel from the image pixels to the object point (Sonka et al., 2008). Image overlapping can be achieved by using a moving platform and a proper frame rate or two or more cameras (Sun et al., 2006; Mills et al., 2010). For example, stereo images allow the measurement of forest tree heights, especially if a DTM is available (e.g., Yu et al., 2015). The tree cover, however, hampers the mapping of the ground surface or lower vegetation in forest from aerial images because the same ground points cannot be seen from multiple images. In airborne laser scanning (see Section 6), ground surface elevation can often be measured even from a single laser pulse. For example, in a boreal forest, part of the laser pulse energy typically penetrates the forest canopy, allowing the measurement of ground elevation.

Due to the passive nature of the imaging method, aerial images in general can be collected only when there is enough sunlight present and, for example, cloudy and foggy weather may prevent collection of useful images. However, images can be taken under cloud cover with current digital cameras. GSD of aerial images can vary from less than one centimetre to more than one metre. Spatial resolution (the size of the smallest detectable object on the ground) is affected by the imaging sensor resolution (the size of the element array), the size of each element in the array, quality of optics of the sensor, atmospheric properties between the object and the sensor, and flight altitude. Previously, the resolution of aerial images has been considered too low for mapping conductors (Baltsavias, 1999). However, currently sub-centimetre GSD can be achieved with helicopter images from altitudes as high as 100 m, in which case even narrow conductors on, for example, 20 kV distribution lines can be recognisable on the images in proper conditions. In addition, the flight altitude of helicopters can be much lower than 100 m (Whitworth et al., 2001; Sun et al., 2006; Ahmad et al., 2013). The image quality is degraded by vehicle motion and vibrations that cause blurring, especially with lenses that have a long focal length (Jones and Earp, 2001).

The angular movement of a helicopter caused by, for example, wind gusts can be compensated by installing the camera in gyro-stabilised gimbals (Jones and Earp, 2001). Considering the spectral information of the images, near-infrared and red channels are typically utilised in vegetation monitoring (Mills et al., 2010; Ke and Quackenbush, 2011). Hyperspectral data have been used by Frank et al. (2010).

4.2. Monitoring of vegetation in power line corridors using aerial images

Monitoring of vegetation, especially trees, is important in power line corridors because vegetation that is too close to the power lines may cause short circuits (Ahmad et al., 2014), blackouts (Ahmad et al., 2014) and even forest fires in dry conditions (Mills et al., 2010). During storms, trees may fall across the power line causing power outages and severe damage to the components. In cold climates, the crown snow-load may bend the trees such that they will be in contact with the power line components and cause the above-mentioned problems.

The studies on vegetation monitoring in power line corridors from aerial images have focused, for the most part, on the extraction, segmentation and classification of trees. Tree species classification can be useful because species that reach a certain height level can be considered undesired whereas in long-term, favouring of low-height species might prevent the growth of higher trees through competition (Li et al., 2012b). In addition, relative positioning with respect to power lines and estimation of heights of trees has been studied. All vegetation studies in power line corridors have utilised fixed-wing platforms. These will be treated in more detail below together with short treatment of general tree extraction from forested areas and the use of hyperspectral images in vegetation monitoring.

In general, several studies have been conducted on the extraction of trees from aerial images in forested areas (see a review of methods in Ke and Quackenbush, 2011). However, in most of the studies, non-forest areas, including power line corridors, have been removed in pre-processing before tree detection (Ke and Quackenbush, 2011). It has also been argued (Mills et al., 2010; Ke and Quackenbush, 2011; Li et al., 2012b) that tree detection in non-forest areas may be more challenging, because they contain more soil, shadows, shrubs and herbaceous vegetation, all of which may contain similar characteristics to trees.

Li et al. (2009) and Mills et al. (2010) studied automatic tree extraction and delineation from multispectral images in power line corridors. They both used a same method that was based on a ratio of NIR and red band reflectances which were given as input to a pulse-coupled neural network, whose output was further improved by morphological processing to achieve the final segmentation. They tested the method in the same power line corridor with multispectral images with a GSD of 15 cm (flight altitude 350 m above ground level). Both achieved a 96% detection rate with 137 (Li et al., 2009) and 129 (Mills et al., 2010) trees. The segmentation accuracies, that is, the proportion of successfully segmented tree crowns (1-to-1 mapping) to all trees, were 81.8% (Li et al., 2009) and 75.2% (Mills et al., 2010). Under-segmentation was the most important error source, but as noted by Mills et al. (2010), the detection rate is more important when considering power line corridor monitoring.

Li et al. (2011a,b, 2012b) investigated tree species classification using multispectral images in power line corridors using the same data as Li et al. (2009) and Mills et al. (2010) (c.f. previous paragraph). They concentrated on three species, Eucalyptus tereticornis, Eucalyptus melanophloia, and Corymbia tesselaris. They utilised support vector machines and compared various features, such as spectral moment features (Li et al., 2011a), pulse spectral frequency features (Li et al., 2011b), texture features (Li et al., 2011a,b) and fusion of colour and texture features (Li et al., 2012b). The classification accuracies of the best features in the comparisons varied between 65% and 95%.

Mills et al. (2010) evaluated the accuracy of stereo vision in tree height estimation and the accuracy of direct georeferencing of images in the relative horizontal positioning of trees with respect to power lines. The GSD of the images was 10 cm in the relative positioning and 5 cm in the height estimation. The average error in the horizontal perpendicular distance of the trees to the power line was 0.7 m. The average error in height was 1.8 m for trees and 1.1 m for pylons. As will be discussed in the next section, 3D modelling of conductors from aerial images is challenging due to lack of texture or other distinctive features in the conductors. However, Sun et al. (2006), Yan et al. (2007b) and Zhang et al. (2007) calculated the distance of the conductors to the ground, vegetation and other nearby objects using stereo vision. In Yan et al. (2007b) and Zhang et al. (2007), the GSD of the images was approx. 5 cm and in Sun et al. (2006) 10 cm. The root mean square error (RMSE) of the 3D model was 0.23 m in Sun et al. (2006), evaluated at 18 test points on ground, building corners and top and bottom of pylons. The RMSE of the distance between objects and power lines was 0.33 m in Yan et al. (2007b).

The use of aerial hyperspectral imaging in vegetation monitoring in power line corridors has been studied only by Frank et al. (2010) (see Section 6.4 for more details). However, in other environments, more studies can be found, for example, on tree delineation and tree species classification (see, e.g., Clark et al., 2005; Bunting and Lucas, 2006).

4.3. Mapping and inspection of power line components from aerial images

4.3.1. Characteristics of aerial images in power line component monitoring

In good conditions and with proper system configuration and high enough resolution, several power line components, such as conductors, pylons, cross arms and insulators can be recognised from the aerial images (Jones et al., 2003; Sun et al., 2006; Yan et al., 2007a; Oberweger et al., 2014). Additionally, condition of some components can be monitored (Ishino and Tsutsumi, 2004; Oberweger et al., 2014). Several factors, however, can make the automatic extraction of power line components challenging. These include complex background, amount and direction of sunlight, background brightness and features similar to those of power line components, weather conditions, and variations in the background due to season (Whitworth et al., 2001; Tong et al., 2009; Tilawat et al., 2010).

The viewing direction of the camera affects what parts of power lines can be observed. Vertical wood poles may be difficult to detect from vertical images even by a human operator due to their small cross-sectional area (Mills et al., 2010). In addition, condition checking of vertically aligned components such as certain types of insulators (Reddy et al., 2013) may require oblique images. In some applications, the camera viewing direction can be adjusted to point to targets of interest (Whitworth et al., 2001).

3D modelling of conductors from aerial images is difficult because conductors are elongated structures with a uniform intensity value (Yan et al., 2007a) and usually do not contain texture or distinctive features in the aerial images. Therefore, it is difficult to find corresponding object points from the conductors in different images that could be used for 3D matching. However, Jóźków et al. (2015) were able to create 3D models of conductors from UAV images (see Section 8.2.1). Also, the 3D positions of the pylon tops and cross arms can be retrieved and these can be used to find approximate catenary curve envelopes if default values for the catenary curve parameters are assumed (Sun et al., 2006). This approach may exhibit accuracy that is sufficient for vegetation encroachment monitoring. In addition, sometimes features, such as spacers are found along the conductors which can be used to create approximate 3D models of the conductors (Zhang et al., 2007).

4.3.2. Mapping of conductors and components attached to them

A few attempts have been made to extract power line conductors from aerial images (Yan et al., 2007a; Tong et al., 2009; Li et al., 2010a; Wu et al., 2010; Ye et al., 2013). In all studies, the images have been collected with a helicopter and most of the studies (Yan et al., 2007a; Tong et al., 2009; Li et al., 2010a; Ye et al., 2013) have concentrated on high voltage transmission lines. Most of the methods in the studies have followed the same basic workflow: at first candidate power line pixels have been retrieved and then lines have been extracted from the candidates (Yan et al., 2007a; Tong et al., 2009; Wu et al., 2010). In some methods, the results have been improved by filling gaps and removing noise (Yan et al., 2007a; Tong et al., 2009). In Ye et al. (2013) particle filtering was applied to track the power line after an initial seed line was retrieved with Hough transform. Li et al. (2010a) used template matching to find conductors from images. The expected number of conductors was given as an input for each image and images from which unexpected numbers of conductors were found were sent to manual checking. The experimental evaluations of the accuracies have been modest in most of the studies and most of the evaluations have been qualitative with a few example images. However, Yan et al. (2007a) and Li et al. (2010a) performed a quantitative evaluation of the accuracy. Yan et al. (2007a) detected 20.6 km of the total of 22.5 km of power line. However, they did not report the amount of false detections. Li et al. (2010a) tested their algorithm with more than 4000 images, found all conductors from the images and achieved a correctness (also known as "precision" or "user's accuracy") of 99.7%.

Following the retrieval of conductors, Li et al. (2010a) extracted spacers along the conductors. They were extracted from the images using the previously extracted conductors as hints for the location of the spacer. Gabor filtering and connected component labelling were utilised in the algorithm. They achieved a completeness (also known as "recall" or "producer's accuracy") of 96.68% with 211 images containing a spacer and the algorithm extracted 47 false positives among a total of 4362 images (1.1% false alarm rate).

Ishino and Tsutsumi (2004) studied the detection of arc marks and cut wires from very high resolution digital videos collected with a helicopter. Their method needed a user given seed point after which the conductor was tracked and its contour retrieved automatically. The arc marks and cut wires were detected using a statistical analysis of brightness and by comparing the extracted contour to an ideal contour, respectively. A set of 6000 images was used to test the method. 362 images contained a damaged conductor and 358 of those were correctly classified. 129 images were falsely classified as damaged.

4.3.3. Mapping of pylons and components attached to them

Most of the studies on the extraction of pylons from aerial images have concentrated either on poles or towers. Sun et al. (2006) extracted wood poles and either the cross arm or the top of the pole from image pairs collected with a fixed-wing aircraft. Their method utilised colour and intensity information and several filters to find pole and cross arm candidates that were matched to each other to find a pole in the image. Jones et al. (2003) detected wood poles in 11 kV and 33 kV power lines and also extracted the position of the base and top of the pole and cross arm using Gabor filters and Radon transform. Tilawat et al. (2010) extracted transmission line towers from aerial images. Their method was based on high density of extracted lines in tower locations. Both Jones et al. (2003) and Tilawat et al. (2010) used a helicopter to collect the images. Sampedro et al. (2014) developed a general pylon extraction and classification method that is not restricted to any specific pylon type (e.g., wood pole or tower). Their learning method utilised local features and multilayer perceptron neural network classifier for the pylon extraction and classification. In most of the pylon studies that contained quantitative analysis, the completeness varied between 75% and 95% (Jones et al., 2003; Sun et al., 2006; Sampedro et al., 2014), and false positive rates between 1.4% and 25% (Sun et al., 2006; Sampedro et al., 2014).

Whitworth et al. (2001) developed a system to aid in the inspection of components attached to wood poles in 11 kV and 33 kV power lines. Their system contained a helicopter-mounted steerable camera whose sightline could be automatically adjusted. They extracted and tracked a top of a wood pole to keep it in the line-of-sight while the helicopter moved along the line. Golightly and Jones (2003) developed more sophisticated algorithms for smooth tracking of the pole and cross arm.

Studies on the extraction and inspection of insulators from aerial images have concentrated on the cap and pin insulators of high voltage transmission lines, in which several identical disc-shaped insulators are arranged in a string. Liao and An (2015) developed an insulator detection method that was based on matching of extracted local feature points with a feature library of insulators. Wu et al. (2012) and Wu and An (2014) developed methods for the extraction of insulator strings and their closed smooth contours. Their methods were based on active contour models. Oberweger et al. (2014) detected cap and pin insulators from aerial images using learning and voting methods and circular descriptors. They also partitioned the insulators into individual caps using Fourier analysis of edge detection and detected faulty caps using elliptic descriptors. In all studies, the aerial images were collected with a helicopter. A large part of the experimental results of the above studies has concentrated on comparing different methods or on analysing the details of the methods and do not evaluate the absolute statistical accuracy. One reason for this may be that there has been a lack of a standard performance metric for the insulator recognition (Oberweger et al., 2014). However, Wu and An (2014) reported an average correctness and completeness of 86% for the segmentation of insulators from 50 images, even though it was not reported how the metrics were calculated. Oberweger et al. (2014) achieved an 80% completeness with a correctness of over 50% with 400 images in insulator recognition. In addition, they were able to detect 95% of the 20 faulty caps from a set of over 11,300 caps. However, the false positive rate was 12%, which resulted in more than 1000 false alarms with their dataset.

5. Thermal images

Thermal imaging is based on the phenomenon that objects emit infrared radiation depending on their temperature. The Stefan–Boltzmann law states that the total energy emitted by the object is a product of the Stefan–Boltzmann constant, and the absolute temperature in power of 4 (Elachi, 1987). Spectral range used for thermal imaging is from 3 μm to 14 μm. Most of the thermal cameras use the atmospheric thermal windows either in the mid-wave infrared (3–5 μm) or in the long-wave infrared (8–14 μm) spectral regions. Cooled infrared cameras are more expensive than uncooled cameras, but their sensitivity and image quality are better with less noise. The highest spatial resolution of infrared images acquired from aerial platforms is <5 cm. Thermal imaging has long been applied to power line surveys from aerial platforms, but also from the ground and inspections robots travelling on conductors, in order to identify potential failures on components, compression splices and insulators (e.g., Zheng and Yi, 2009). Devices operating at a higher temperature (electrical hot spot) can be mapped because they radiate energy in the long wavelength infrared spectrum.

Only few research articles deal with thermal imaging in power line monitoring. However, there are many commercial uses for aerial infrared thermography using various platforms, and the surveys of high voltage electric utility transmission and distribution lines are among them (Stockton and Tache, 2006). Electrical faults on high voltage electrical transmission lines can be detected rapidly from the air. However, the study by Stockton and Tache (2006) showed that even from short distances, accurate temperature measurements of the electrical faults were impossible to quantify. This was due to the large measurement spot size compared to the small target size and long measurement range, object reflection, and weather conditions. In this review, patents were not included in the analysis, but in the field of thermal imaging, one patent could be mentioned. Fernandes (1989) invented a monitoring system using a unique remotely piloted drone with different sensors, including thermal infrared imaging. UAV thermal imaging is perhaps one of the first UAV-based operational applications related to power line corridor surveys. More information on recent UAV studies can be found in Section 8.

Blazquez (1994) used an airborne Probe Eye Scanner/Normal Color Video System (PESNVS) in an exploratory test. Faulty components operating above the normal temperature on high-voltage transmission lines were detected, and the results were confirmed by ground surveys. Degradation of the mechanical structure of power line components and also deterioration in their electrical integrity result in higher temperatures than those observed in the adjacent components. Image interpretation was carried out visually. Frate et al. (2000) evaluated the overhead line and joint performance using high-definition thermography that utilised ground based measuring methods. The ultimate objective was to develop a method that would yield the actual temperature of a joint. Comparisons between simulations and the measured temperature were included. A computational method was used to assess the conductor temperature by using the operating current, the wind speed and direction, and the outdoor temperature as the input data. Qin et al. (2000) gave theoretical aspects of the heat conduction of electric power lines in their article. An uncooled infrared camera for contactless temperature measurements of electric power systems was described.

In conclusion regarding airborne thermal images, we can say that relevant temperature anomalies can be detected in the electric lines and devices, but according to available scientific references, accurate temperature readings are difficult to get. Despite the limited number of scientific studies in this area, thermal imaging has, however, become an important tool used by utility companies. They use thermal imaging checks before beginning of maintenance work in order to avoid costly service interruptions. It is expected that sensor miniaturisation is leading to increasing interest in multisensoral UAV surveys including both thermal imaging and laser scanning.

6. Airborne laser scanner data

6.1. Basic principles of airborne laser scanning

Airborne Laser Scanning (ALS) is an active remote sensing technique based on Light Detection and Ranging (lidar) measurements from an aircraft (Beraldin et al., 2010). The precise position and orientation of the sensor is known from GNSS (Global Navigation Satellite System) and IMU (Inertial Measurement Unit) measurements, and therefore the position (x, y, z coordinates) of the reflecting objects can be determined. The result of laser scanning is a georeferenced point cloud of lidar measurements. In addition to the coordinate information, the intensity of the returned pulses is normally available. Laser scanner systems can typically record up to four return echoes for each pulse sent to the target. For example, the first echo can return from the tree canopy or a power line and the last one from the ground surface. The number of returning echoes and the height differences between them depend on the type of the surface, and this information can be used in the interpretation of the data. In the case of full-waveform laser scanning, the full shapes of the returning echoes are registered.

The point density in ALS, especially in low-altitude power line monitoring, is typically in the range of dozens of points per m^2. However, point densities of even hundreds of points per m^2 can be achieved from helicopters. The absolute planimetric (xy) accuracy of ALS data is typically about 5–10 cm. An absolute height accuracy of about 2–5 cm can be achieved on hard surfaces. Such point density and accuracy allow detailed mapping and monitoring of power lines and their surroundings. Detection and 3D reconstruction of individual conductors and trees becomes possible. Example of ALS data acquired from a power line corridor can be seen in Fig. 4. ALS data can be acquired from helicopters or fixed-wing aircraft. In the case of power line studies, helicopters have been most often used because they can follow the power line corridors in a more flexible way and measurements from very low altitudes can be done. In many articles, however, the platform used in data acquisition has not been specified.

6.2. Mapping of power lines from airborne laser scanner data

6.2.1. Methods for power line classification

Most of the studies using ALS data have concentrated on developing automated classification and reconstruction methods for the extraction of power line components, especially conductors. A typical process includes generation of a DTM, classification of the laser data to distinguish power line points from other objects, especially vegetation, and 3D modelling of the individual conductors. Detection of pylons has also been included in some studies (e.g., Sohn et al., 2012; Guo et al., 2015).

Classification to distinguish power lines from other objects has been typically based on line detection or analysis of the structure of the point cloud. Useful features for classification can also include, for example, the difference between first and last pulse heights, and the intensity. Axelsson (1999) used information on multiple echoes and intensity to separate power lines points from vegetation. Refined classification of power lines was achieved by searching for parallel, linear structures using Hough transforms. Melzer and Briese (2004) applied iterative Hough transform to a filtered point cloud. Clode and Rottensteiner (2005) separated power lines and trees by analysing intensity values and height differences between first and last pulse data. It was assumed that trees have many points with a large height difference between first and last pulses in a local neighbourhood, while power lines only have a few such points. Power lines also had low intensity values. The classification method was based on the Dempster-Shafer theory. McLaughlin (2006) classified laser points into three classes: transmission line, vegetation, or surface. Surfaces included both the ground and roofs of buildings. The structure of the point cloud was modelled within ellipsoidal neighbourhoods by using the covariance matrix, and a Gaussian mixture model was applied in the classification. Liu et al. (2009) used intensity data and the Hough transform to detect conductors. Zhu and Hyyppä (2014) proposed a method that first identified candidate power line points by using statistical analysis of the point cloud and then refined the

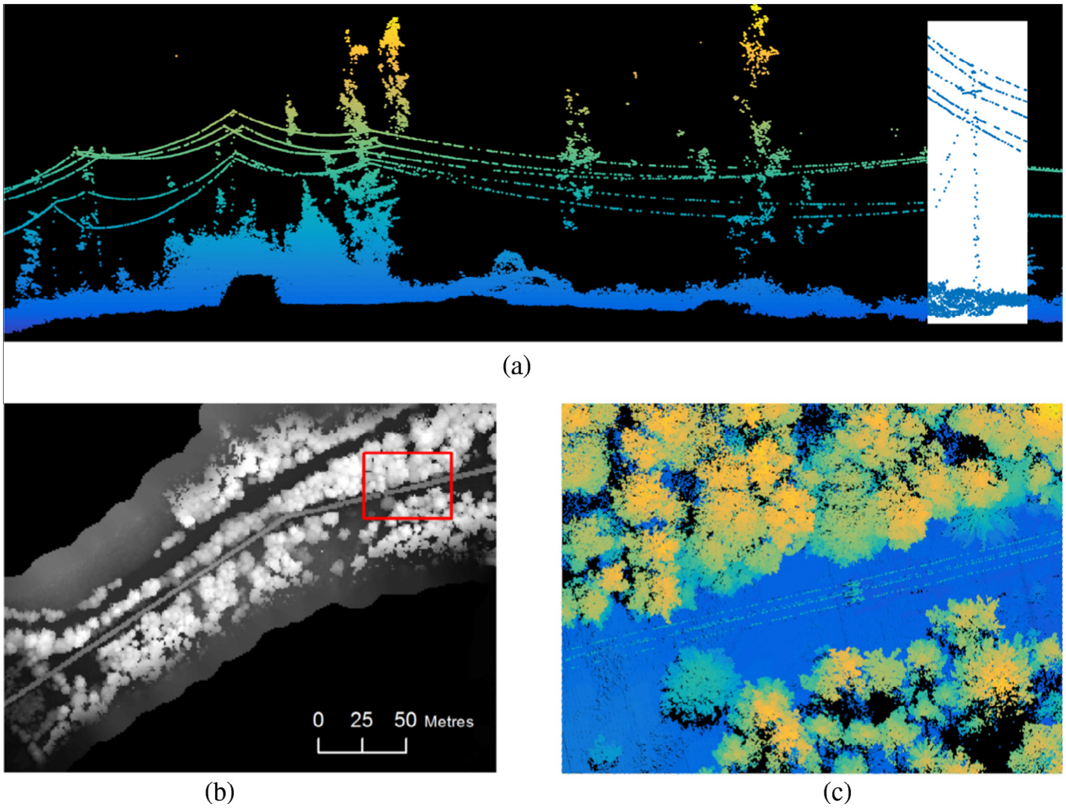

Fig. 4. ALS data from a power line corridor acquired from a helicopter. (a) Side-view of the point cloud showing individual conductors, poles and vegetation. Colouring of the points is based on their height values. The small image on the right shows a closer view to one pole, cross arm, conductors and stays. (b) Raster DSM clearly showing the location of the corridor. The DSM presents the highest elevation value for each 1 m × 1 m cell. (c) The point cloud seen from above. Part (c) covers the area of the red rectangle in (b).

results by image-based processing that analysed the 2D geometric properties of objects.

Some recent studies have applied machine learning algorithms and a larger number of features than the above-mentioned studies. For example, Kim and Sohn (2013) applied the random forests classifier and 21 features calculated from ALS data for classifying conductors, pylons, vegetation, buildings and low objects. The features described the spatial distribution of the laser points and they were calculated for each point by using spherical and cylindrical neighbourhoods. Guo et al. (2015) discussed classification of ALS point clouds by using a JointBoost classifier and 26 features. Graph-cut segmentation was also applied to improve the results. Classes of interest included buildings, ground, vegetation, power lines, and pylons.

6.2.2. Methods for power line reconstruction

Power line conductors between two adjacent pylons (i.e., over a span) have the shape of a catenary curve and can thus be modelled by fitting catenary curves to the detected power line points. Sophisticated methods including several different processing steps have been presented to group detected power line points or lines in individual spans and to model the conductors. For example, Melzer and Briese (2004) grouped the detected lines into corridor segments and computed the intersections of the segments. The points belonging to a single corridor segment were then assigned to individual conductors, and the conductors were modelled with catenary curves. Several computation methods were used in the process. McLaughlin (2006) first calculated local models for sections of transmission lines in ellipsoidal neighbourhoods. Complete spans were then detected iteratively by adding local affine models, and the catenary parameters were progressively refined. Jwa and Sohn (2012) presented a method based on piecewise catenary curve model growing. Power line candidate points were first extracted by using three different operators for linear feature extraction. The candidate points were used as seed points to generate primitive models. These models were then grown progressively by producing hypothetical growing models and selecting the optimal ones. Recently, Guo et al. (2016) presented a reconstruction method that uses the properties of a conductor group between two neighbouring pylons to improve reconstruction results. It is assumed that conductors in one group are nearly parallel with the same direction and sag, and this information can be used, for example, in setting initial parameters for the reconstruction.

6.2.3. Quality of the results

As power lines are very narrow objects, the density of the laser points should be relatively high to achieve good results in power line extraction. Surrounding vegetation and complexity of the power line network can cause additional challenges in the extraction. McLaughlin (2006) tested his method with about 13.8 km data acquired from a helicopter (includes both training and testing data). The point density was approx. 2.5 points/m^2. The percentage of correctly identified transmission line points was 86.9%, and the false positive rate was 0.20%. The percentage of correctly extracted transmission line spans was 72.1%. According to the author, the sparseness of the data was the primary limiting factor for the classification accuracy. Kim and Sohn (2013) achieved an overall classification accuracy of 91.04% (sample-weighted accuracy, i.e., the percentage of correctly classified points to entire number of points; five classes included). In this case, the point density was 25–30 points/m^2. The data analysed in the study covered a total length of 1.9 km in California and were acquired from a helicopter. There were both transmission lines (115 kV and 230 kV) and distribution lines (below 110 kV) in the area. Jwa and Sohn (2012) also used laser data acquired from a helicopter and a test area in California. The average point density was 24 points/m^2, and the length of the test area was approx. 640 m. The area included complex structures of power lines. According to visual inspection, the percentage of complete models in the results was 96%. Completeness and correctness for power line points captured by the models were 99.5% and 92.82%, respectively. RMSEs of the produced power line models were 5.2 cm in 3D and 2.9 cm in 2D. Errors in the results occurred, for example, in a sub-area with vegetation. Zhu and Hyyppä (2014) reported a classification accuracy of 93.26%. This was the average correctness of classified power line points in six test areas in Kirkkonummi, Finland. The total length of power lines under study was approx. 1.8 km, and the power line corridors were surrounded by forest. The density of the laser points was 55 points/m^2.

Practical studies using commercial software packages have been carried out, for example, by Otcenasova et al. (2014), who tested TerraScan software for detecting conductors in the Slovak Republic. The point density of the dataset was originally approx. 30 points/m^2, but a reduced point density of approx. 5 points/m^2 was also tested. According to the authors, the lower density was also sufficient for automatic conductor detection, although the number of errors was higher (accuracy measures not given in the article). The most problematic part of the detection process was identification of towers, which had to be carried out manually. Lu and Kieloch (2008) discussed the accuracy of transmission line modelling based on ALS data, considering the effects of ambient air temperature, electrical load, solar radiation, wind, and conductor size on the base conductor temperature.

6.3. Mapping of vegetation from airborne laser scanner data

Ko et al. (2012) used high-density laser scanner data (about 40 pulses/m^2) to identify single trees that threatened transmission line infrastructure. Geometric features were calculated for trees and used as input data for tree species classification with the random forests classifier. Based on the results, it was possible to identify trees growing within the minimum vegetation clearance distance and to identify tall trees that could fall onto the conductors. The dominant growth directions of the trees were also determined to identify trees leaning towards the infrastructure. Some studies have combined aerial images and ALS data in vegetation monitoring in power line corridors (Frank et al., 2010; Li et al., 2012b). These studies will be discussed in the following section. Ussyshkin et al. (2011) discussed the use of Optech laser scanner data in practical monitoring tasks such as catenary modelling for thermal up-rating and vegetation encroachment analysis.

In general, forest monitoring from ALS data is a topic of active research, and methods for detecting and modelling individual trees are available (Hyyppä et al., 2012). It has also been shown that accurate results on the location and size of trees can be achieved (Kaartinen et al., 2012b). The same methods can be directly applied to the monitoring of trees in power line corridors. Repeated ALS measurements allow high-quality measurement of forest growth (Yu et al., 2005) and estimation of future threats to power lines. Previous studies have also demonstrated the high information content of ALS full-waveform data for forest applications (Hollaus et al., 2014). More references of forest monitoring can be easily found from Hyyppä et al. (2012) and Kaartinen et al. (2012b).

6.4. Comparison or fusion of aerial images and airborne laser scanner data in power line monitoring

A few studies have either compared ALS and aerial images or utilised their fusion in power line monitoring applications. Most of these studies have concentrated on vegetation.

Mills et al. (2010) compared multispectral aerial images to ALS point clouds (both collected with a fixed-wing aircraft) in estimating the heights of trees and poles and relative position of trees with respect to power lines. The relative position was divided into along-track distance (the distance to the closest pole along the line) and cross-track distance (perpendicular horizontal distance to the power line). The average point density of the ALS point clouds was 9 points/m^2. In relative positioning, the GSD of the aerial image was 10 cm and in height estimation they used 5 cm GSD images for poles and 15 cm GSD for trees. ALS was found to be more than three times more accurate than aerial images both in relative positioning and in height estimation. The average accuracy of ALS was better than 0.5 m for both relative positioning and height estimation. They found that 15 cm GSD was not enough to find poles reliably from images and that even in laser data there was a shortage of hits from poles. In many cases, the response came only from the cross arm and not from the pole itself. A comparison between aerial images and ALS data in the estimation of tree and pole heights was also presented by Cai and Walker (2010). Similarly to Mills et al. (2010), they concluded that ALS data gave a clearly higher accuracy of height estimation.

Li et al. (2012b) tested a fusion of multispectral images and ALS in tree segmentation. They utilised the method of Li et al. (2009) to perform a preliminary segmentation of trees from multispectral images and then overlay a 2.5D height image, extracted from ALS data, on top of the segments to remove low vegetation segments that resembled trees in the multispectral images. They were able to improve the accuracy of segmentation by 9.5 percentage points compared to Mills et al. (2010) who did the segmentation only with the multispectral data in the same test area, however, they did so with different trees. According to Li et al. (2012b), point density of ALS is critical for the fusion process because small trees may be missed if the point density is too low. Li et al. (2012b) and Mills et al. (2010) used the same multispectral and ALS datasets which were collected in separate flights using fixed-wing platforms.

Frank et al. (2010) investigated the use of aerial hyperspectral images and ALS data in the land cover and tree species classification near 66–240 kV lines. The GSD of the hyperspectral data was 50 cm and the GSD of the ALS data 15 cm (point density 28 points/m^2). They found that hyperspectral data provided 29 percentage points higher overall accuracy than ALS and that their fusion yet improved the accuracy by 8.5 percentage points. Kersting and Centeno (2007) presented an object-oriented approach to classifying power line corridors in urban environments. Rasterised height and intensity data from ALS and orthorectified aerial image data were used as input data for segmentation and classification. Buildings, trees, distribution lines and different types of ground surfaces were considered.

7. Land-based mobile mapping data

7.1. Basic principles of mobile mapping

A land-based mobile mapping technology is based on integration of various positioning, navigation and imaging data collection sensors constituting a mobile mapping system (MMS) that is mounted on a kinematic platform such as a car. Imaging data in the following discussion include various types of images and point clouds. The most important sensors to collect these data are cameras and laser scanners (El-Sheimy, 2005; Petrie, 2010). GNSS and IMU are the most important parts of the navigation sub-system (El-Sheimy, 2005) that produces the MMS trajectory and sensor orientation during the data collection. System position and orientation at any given time is used for direct georeferencing of the collected imaging data into a world coordinate system (Puente et al., 2011). In addition to cars, the platforms that give mobility for the system can be, for example, all-terrain vehicles (ATV), boats, and backpacks carried by persons (El-Sheimy, 2005; Kukko et al., 2012). The earliest applications of MMS to power line mapping date back to the 1990s. The TruckMap van-based system (Reed et al., 1996) contained several GPS receivers for the platform position and attitude determination and a manually controlled laser range finder with which the 3D coordinates of objects could be measured.

An MMS whose main imaging component is a laser scanner is often called a mobile laser scanning (MLS) system. Compared to ALS (typical point density 5–100 points per m^2), MLS collects much denser point clouds (up to thousands of points per m^2 at a 10 m distance from the scanner) with much higher detail due to the narrow beam divergence angle. The accuracy of the point clouds is usually determined by the accuracy of the GNSS-INS solution, as in ALS. If enough satellites are available, 2–3 cm accuracy can be achieved with the best MLS systems in urban or semi-urban environments (Haala et al., 2008; Kaartinen et al., 2012a) or with a backpack personal laser scanning (PLS) system in an open valley (Kukko et al., 2015). In recent studies of full grown forest canopy cover, the post-processed GNSS-IMU positioning was found to provide 0.7 m absolute accuracy levels for MLS (Liang et al., 2014a; Kaartinen et al., 2015) and PLS (Liang et al., 2014b). In challenging satellite visibility conditions, the absolute accuracy can degrade to several metres (Gu et al., 2015), but even then the relative accuracy between neighbouring points can be better than 1 cm (Kaartinen et al., 2012a). However, even within a short time interval the relative accuracy is drastically dependent on the quality of the IMU sensor, and sub-centimetre relative accuracy is not typically achieved with low cost IMU sensors. GNSS outages are common, for example, in forests and urban canyons. High-density ALS data can be used to improve the accuracy of georeferencing of MLS data in areas where satellite visibility is poor at ground level, because airborne systems receive good satellite signals in almost all conditions.

Because of panoramic imaging geometry, MMS is able to see certain objects better than downwards-looking airborne technologies. For example, vertical pole-like objects, such as pylons, that may be difficult to detect with airborne systems (Ahokas et al., 2002; Mills et al., 2010) can be extracted with higher accuracy using MLS (Lehtomäki et al., 2010; Cabo et al., 2014). In addition, details inside the forest canopy can be retrieved, which is not possible with ALS data. The beam size is smaller with MLS than with ALS, helping to detect the object in finer detail. The ranging accuracy of MLS is higher than in ALS, and this enables extraction of more accurate features, such as surface normals. Also, conductors that are on top of each other may be more easily extracted using MLS than ALS, which may fly straight on top of the power lines (Cheng et al., 2014). These considerations are, for the most part, also relevant for the image-based MMS systems, when compared to airborne systems. Scanning of a power line corridor with a backpack PLS laser scanning system is shown in Fig. 5. Data acquired with the system can be seen in Fig. 6.

7.2. Mapping and inspection of power line components from mobile mapping data

Only a few studies yet published have concentrated on the extraction of power lines from MLS point clouds. Most of the studies do not contain statistical analyses of the accuracy of the methods or have rather small test sets. In addition, all studies have concentrated on urban environments, due to the obvious mobility limitations of a standard MLS on a car, but also because of fairly recent emergence of the technology. Kim and Medioni (2011) extracted power line conductors from a point cloud that was a fusion of MLS and ALS. They used tensor voting to extract linear points and then applied a growing method to extract conductors. Lam et al. (2010) extracted pylons using Ransac and then power lines by selecting all points inside a box that spanned the space between two consecutive pylons. Guan et al. (2016) extracted and modelled power lines using several filters, Hough transform, clustering and catenary curve fitting. The point clouds were collected using a RIEGL VMX-450 system and the average point density was approx. 290 points/m^2. They tested their methods on two road stretches whose total length was 185 m and achieved an average completeness of 92% and an average correctness of 99%. Cheng et al. (2014) extracted and modelled power lines using several filters, Hough transform, clustering of power line spans and modelling of conductors using local line and parabola fitting and growing. Their methods extracted 94% of the power lines in a 4 km long test area while the correctness of the detection was 99% and the accuracy of the clustering 97%.

Fig. 5. Scanning of a power line corridor with a backpack PLS laser scanning system (FGI AkhkaR2).

To our knowledge, only Murthy et al. (2011) have studied the monitoring of power lines using cameras attached to a moving land-based vehicle. Their main goal was to analyse the condition of insulators in urban and suburban environments along the roads. They used a template design for the tracking of poles, and wavelet features and a hidden Markov model to classify broken insulators.

Concerning the detection of pylons from MLS point clouds, several studies have concentrated on the automatic detection of general vertical pole-like objects (e.g., traffic signs, lamp posts and tree trunks). For example, Lehtomäki et al. (2010) and Cabo et al. (2014) reported completeness between 67% and 92% and correctness between 82 and 84% in urban and suburban environments. In addition, detection of pole-like objects from mobile mapping image sequences has been studied and detection rates of over 90% have been achieved (Doubek et al., 2008).

7.3. Mapping of vegetation from mobile mapping data

To our knowledge, no studies exist that have used MMS in the mapping of vegetation in power line corridors. However, in other environments such studies exist. For example, Liang et al. (2014a) studied the detection of trees in a forest environment using MLS and Puttonen et al. (2011) studied tree species classification using MLS, mobile terrestrial hyperspectral images and their fusion in an urban garden. Liang et al. (2014a) also found that MLS data allow assessment of tree diameters. Yang et al. (2012, 2015) studied the extraction of urban trees using MLS and fusion of MLS and images, respectively. Similar approaches could be used to monitor vegetation in power line corridors.

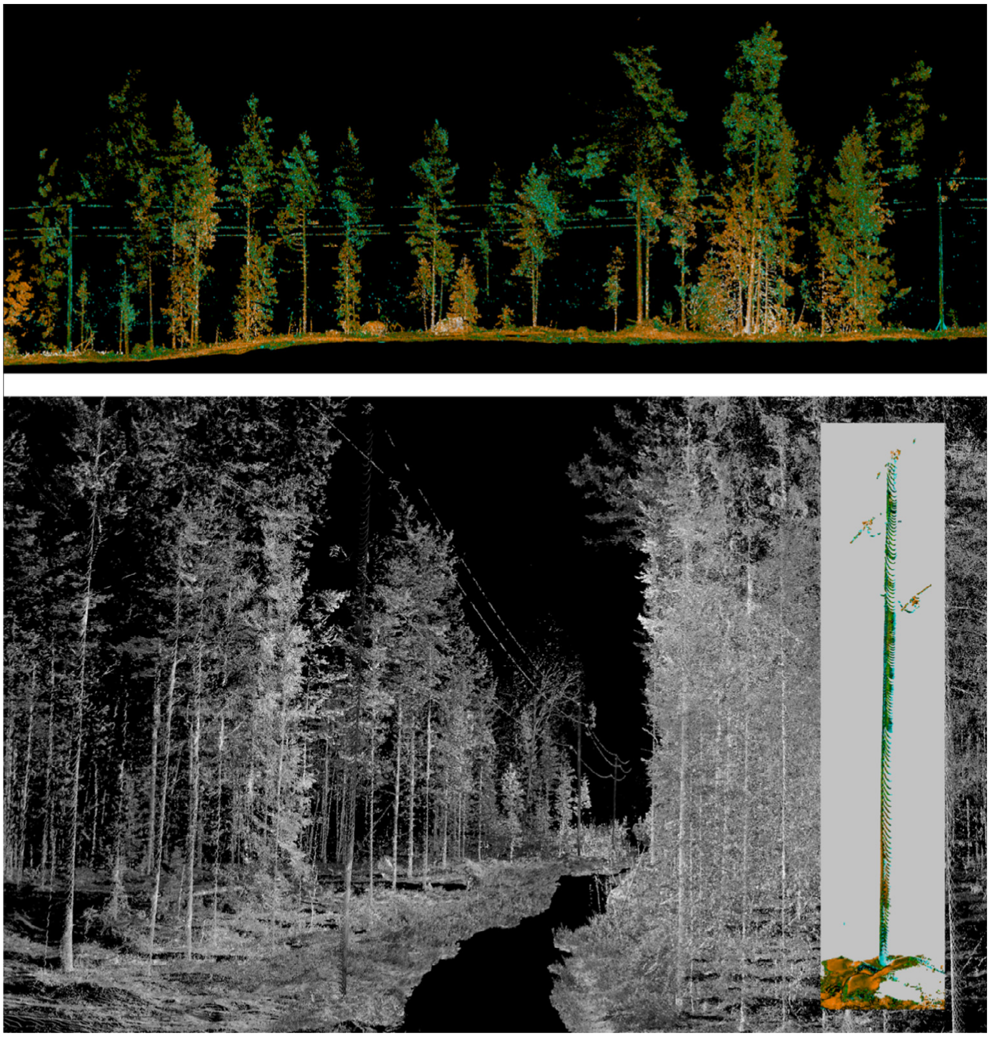

Fig. 6. Power line captured with the backpack PLS system FGI AkhkaR2. The conductors, insulators and poles are detectable from the data, as well as the vegetation around the components.

8. UAV data

8.1. Background on the use of UAV data

The use of UAVs provides a flexible approach to acquire high-resolution airborne data on power lines. The benefits of UAVs include, for example, their ability to fly close to the power lines (Li et al., 2010b) and their significantly lower operating costs when compared to helicopters (Cai and Walker, 2010). The number of research articles dealing with UAV-based power line monitoring has clearly increased during the last few years, although older studies can also be found (e.g., Del-Cerro et al., 2001). A similar trend can be observed in photogrammetry and remote sensing in general. Development of UAVs (also called unmanned aerial systems (UAS), aerial robots, drones, or remotely-piloted aerial systems (RPAS)) is a growing field with various potential applications and an increasing number of published scientific studies (Colomina and Molina, 2014). During recent years, the technological advances related to UAV components and battery technologies have been rapid, which have improved the feasibility of UAV-based data acquisition for power line inspection. The development of lithium polymer battery technology has been very important in improving the endurance of UAVs as combustion engines are often unsuitable for UAV use because of the high-amplitude vibrations produced by the engine. The maximum flying time depends heavily on the type of platform and the weight of the payload, but it typically varies between half an hour and two hours. Also the improved availability of lightweight sensor systems and the development of UAV-related legislation have contributed to the applicability of UAVs in commercial applications. The regulations vary significantly between countries and while some countries, such as the United States, have all but banned commercial operations, some, for example Finland, are very liberal and encourage the commercial use of UAVs. Links to regulations in different countries have been listed by ISPRS ICWG I/Vb (2016).

Different UAV platforms have been applied to power line surveys. Generally, fixed-wing UAVs need to fly higher and faster and they are suitable for vegetation monitoring and rough inspection of long power lines, while helicopter and multi-rotor UAVs can be used to acquire detailed pictures by hovering in the air close to the objects (Hrabar et al., 2010; Deng et al., 2014). Deng et al. (2014) suggested a multi-platform system consisting of different types of UAVs for different purposes.

In power line monitoring, applications and approaches basically similar to those discussed previously in the aerial image and ALS sections are possible with UAV data. In addition, the agility of these systems compared to larger aerial systems allows more flexible approaches. Toth and Gilpin-Jackson (2010) discussed a variety of possible applications of UAVs in transmission line monitoring. In addition to structural inspection and vegetation monitoring tasks, these included various tasks in damage assessments after extreme weather events or other incidents. For example, UAVs could be used by field personnel to assess road damage ahead, or they could be deployed in continuous readiness at strategic locations and used for rapid fault and damage assessment of the network when needed. Toth and Gilpin-Jackson (2010) also presented a list of requirements for UAVs by British Columbia Transmission Corporation, Canada. They concluded that UAVs have a definite appeal for civilian applications, but there are still significant technical, operational, regulatory and financial issues to be solved. Hrabar et al. (2010) also listed requirements for UAV systems used in power line inspections.

In practice, most of the published studies based on UAV data have used optical images, and many of them have concentrated on line detection methods. In addition to monitoring purposes, line detection is needed for navigation of the UAV along the power line, assuming that prior information on the location of the line is not available. UAV-based laser scanning has been mentioned only in a few papers. Further development of small laser scanner systems and UAVs can make this technology a powerful alternative in the future (Li et al., 2012b). Fig. 7 shows a UAV system flying over a power line and laser scanner data acquired with such a system. Katrašnik et al. (2010) reviewed the use of mobile robots, including UAVs as flying robots, in power line inspection. The review concentrated on technical aspects related to the UAVs themselves such as position and attitude control and guidance system, which are important issues in UAV-based inspection. Montambault et al. (2010) presented a review on vertical take-off and landing (VTOL) UAVs for the inspection of power utility assets. Their review also concentrated on the UAV systems. Unlike these previous reviews, our review focuses on power line monitoring applications and thus concentrates on UAV studies with a clear monitoring aspect.

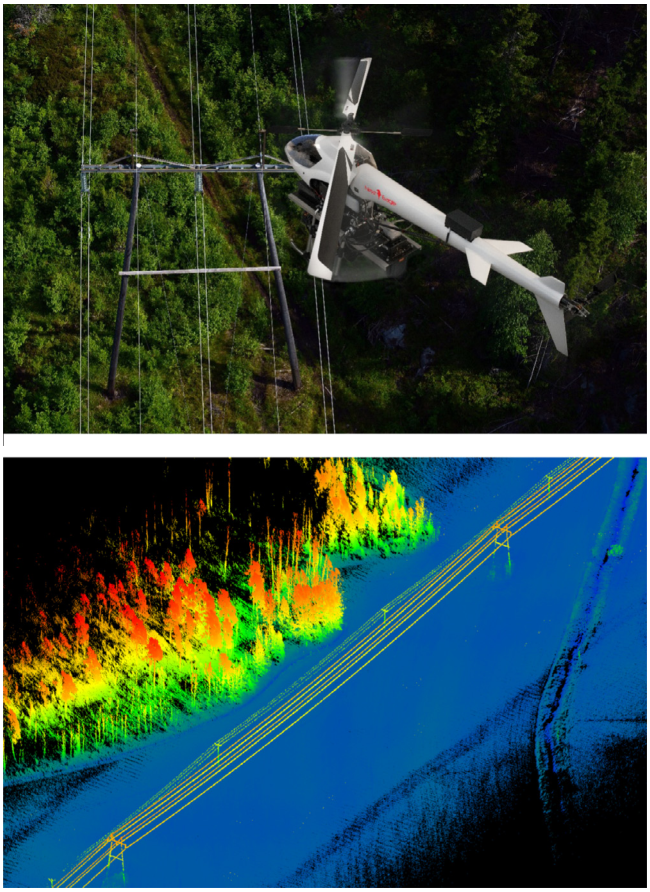

Fig. 7. Top: A Next Eagle UAV system flying above power lines. Bottom: Laser scanner data acquired with the FGI Sensei UAV system version 4.0 using VLP-16 as the laser scanning system.

8.2. Mapping and inspection of power line components and vegetation from UAV data

8.2.1. Methods for object extraction

Several studies can be found on power line extraction from UAV images. These studies typically concentrate on the details of the line detection methods. The results have often been illustrated with a few figures without numerical quality evaluation. For example, Li et al. (2010b) presented a method that included a pulse coupled neural filter to remove noise and generate an edge map, Hough transform to detect straight lines, and knowledge-based line clustering to refine the results. The method was tested with images acquired from two fixed-wing UAV platforms, and the results were shown for a few images covering small areas. Sharma et al. (2014) presented an approach that included adaptive thresholding to isolate power lines in varying light conditions, a morphological operator to find candidate lines and a heuristics-based method for actual detection of power lines. The method was tested with video frames over a 320 m section of a power line. The data were acquired from a fixed-wing mini-UAV. According to Sharma et al. (2014), there were no missed detections of important line segments and false positives occurred in about 3% of frames. Recently Jóźków et al. (2015) discussed 3D modelling of power lines from images acquired from a UAV. Dense image matching was used to produce a point cloud that allowed 3D modelling of conductors with catenary curves. The approach requires images with high overlap and appropriate resolution. The width of the conductors should be several pixels to present sufficient texture for matching.

Campoy et al. (2009) discussed the use of computer vision on board UAVs. Power line inspection was discussed shortly as one application area. Castellucci et al. (2013) classified oblique colour images taken from a UAV to detect poles and their cross arms. Neural network classification and some additional processing stages were used. The percentages of correctly detected poles and cross arms were 70% and 72%, respectively. Martinez et al. (2014) presented an approach for real-time autonomous detection and tracking of electric towers. Methodology used in the study included, for example, neural network classification to detect towers and a hierarchical tracking method designed for real-time tracking. The study included quality analysis using videos from manned helicopter inspections. In the analysis of thousands of image frames, towers were detected in nearly 90% of frames containing towers. The main motivation of the study was related to automating the power line inspections from UAVs. The study by Cai and Walker (2010) concentrated on height determination from sequential aerial images taken from mobile platforms such as UAVs and small airplanes. A new stereo matching algorithm was presented. In experiments, images taken from small airplanes with downward-facing cameras were used. The heights of trees and power line poles were estimated, and the average errors were 1.8 m and 1.1 m, respectively. The flight altitude was 230–280 m above ground level. Detection of insulators from UAV data has also been discussed (Li et al., 2012a).

8.2.2. Systems for real-time monitoring

Larrauri et al. (2013) described a system called "RELIFO" for automatic and almost real time inspection of power lines from UAV data. The article concentrates on presenting the functionality of the system and algorithms developed for detecting power lines, vegetation and buildings and calculating distances between them. The system generates reports and alarms about detected problems and sends them to a control centre. The system uses visual and thermal video camera data. The visual data are used to detect vegetation and buildings close to power lines and calculate the distance between them and the conductors. For example, identification of power lines is based on a line detection approach, laser altimetry data are used to measure heights above the ground, and stereoscopic analysis is used to calculate distances between objects. The thermal image data are used to detect bad conductivity and hotspots in the power lines, transformers and electrical substations. Quality analyses of the results produced by the algorithms are not presented in the article. Luque-Vega et al. (2014) also described a UAV system with colour and thermal infrared cameras. Vision algorithms running in the ground control station are planned to report anomalies in real time. The vision system described in the article concentrates on qualitative inspection of joints in the power lines by analysing their temperature. Stereoscopic analysis is first used to remove background from the thermal images. The joints have higher temperature than other parts of the towers and can thus be detected as hot spots in the thermal images. Temperature differences between joints are used to detect faults. Quality analyses of the results were not presented.

8.2.3. UAV-based laser scanning

Ax et al. (2013) presented the use of laser scanner data from a UAV helicopter for vegetation controlling at high-voltage transmission lines. The article discusses the devices used, flight planning and operation. Post-processing is used to generate a 3D point cloud, and the point cloud is then imported into an existing model of the transmission line. In the 3D model, distances between the vegetation and conductors can be calculated. The developed low-weight system provided points with positional deviation less than 75 cm. Taking into account that the security distance between trees and conductors at the line under study was 4 m, Ax et al. (2013) concluded that the accuracy achieved in the study was sufficient for the application. Jaakkola et al. (2010) evaluated the accuracy and feasibility of a mini-UAV-based laser scanning system for tree measurements. The standard deviation of individual tree heights was approx. 30 cm. The same technology could also be valuable for applications in power line monitoring. Jaakkola et al. (2010) also demonstrated a method to derive the biomass change of a coniferous tree from a multitemporal laser point cloud with an R^2 value of 0.92. In Wallace (2014), use of UAV laser scanner data resulted in 98% of trees being repeatedly and correctly delineated from the point cloud, and trees measured with a location accuracy of 0.48 m and a crown area accuracy of 3.3 m^2.

9. Other approaches and studies

In addition to the remote sensing methods presented above, many related approaches can be found in the literature. These include, for example, climbing robots and the use of ultraviolet (UV) images, microphones, static terrestrial laser scanning (TLS), and various camera-based monitoring approaches. The basic ideas behind the use of various sensing techniques in the inspection of transmission lines were discussed by EPRI (2008).

Climbing robots travel on conductors and can be equipped with sensors and tools for power line examining, and small repair work and maintenance. Montambault and Pouliot (2003) presented some maintenance jobs a robot LineROVer was able to do. These included visual and infrared inspection, evaluation of compression splice conditions (resistance measurements), replacement of conductors and ground wires (live), and cleaning and de-icing of conductors. Montambault and Pouliot (2006) presented LineScout technology. This robot can travel on a single live line up to 735 kV. Expliner is a Japanese robot developed in 2008 (Debenest et al., 2008; 2010). Its four sensing units include visual cameras to image the entire surface of the wire, and laser sensors to detect changes in the wire diameter due to internal corrosion. Obstacles such as insulators, spacers and counterweights cause motion problems for a robot when it is crawling forward on overhead transmission lines. Methods have been presented to overcome these obstacles (Tang et al., 2004; Debenest et al., 2008). Katrašnik et al. (2008) proposed a climbing-flying robot that would use a helicopter for flying over obstacles and a special drive mechanism for travelling on conductors. Some computer vision -based approaches have been used in the analysis of data acquired by robots, but there is still need for further development of automation (Mirallès et al., 2014).

An ultraviolet light camera can be used for detecting corona effects in power line components because corona energy radiates mainly at a spectral range of 300–400 nm having their peak values at 340 and 360 nm. For example, Vasquez-Arnez et al. (2010) used ultraviolet and infrared cameras to inspect the presence of corona on 138 kV lines. Ninedorf et al. (2008) discussed the use of ultraviolet and infrared imagery in high-voltage power line survey. They developed a portable daylight corona camera. An ultraviolet image is overlaid onto infrared as well as a visible colour image. Different layers help to locate the corona effect and the ultraviolet/infrared image allows analysis to determine if there is damage and the severity of the phenomenon.

Several other interesting studies can also be found. For example, Ha et al. (2012) used a microphone array for fault detection on transmission lines and an infrared thermal imaging camera and a charge-coupled device (CCD) camera for verification. Thickness of ice and snow coverage on power transmission line conductors and insulators has been studied using cameras mounted on transmission line towers (see, e.g., Gu et al., 2009; Yu and Peng, 2010; Zhong et al., 2013). Automated monitoring of insulators has been discussed in several articles. The main idea in these approaches is to take images of the insulators at regular intervals, and to use automatic classification methods to detect broken insulators. For example, Reddy et al. (2013) used cameras mounted on poles. Jiang et al. (2011) discussed the measuring of insulators by using a photogrammetric method. Cameras on a tripod were used in the experiment. The objective of the work was to prevent flashovers caused by pollution. Arastounia and Lichti (2013, 2015) studied the extraction of insulators and recognition of key components (fences, cables, circuit breakers, etc.) of an electrical sub-station from TLS point clouds. They achieved promising results with multi-scan datasets of varying point density. Gonzalez-Aguilera et al. (2012) constructed CAD (computer-aided design) models of an electrical sub-station semi-automatically from a fusion of TLS point clouds and photographs. Ahmad et al. (2014) proposed a method for vegetation encroachment monitoring of transmission lines using a single 2D camera. A single camera monitors dangerous vegetation under the transmission lines. A camera is mounted on the power pole and acquires images and transmits them wirelessly to a base station. Image pattern recognition techniques are used to identify possible dangerous vegetation and the personnel at the base station can take appropriate action.

10. Discussion

10.1. Summary of remote sensing methods in power line corridor surveys

As described in the above sections, various remote sensing methods have been applied to power line surveys. Table 1 summarises the main applications involving different remote sensing data sources in the published research literature. The specific advantages and challenges of the data sources in the context of power line monitoring are also listed in the table. Considering the advantages and challenges, the list is not limited to published power line studies, but the general properties of the data sources are taken into account to evaluate their potential for power line monitoring.

10.2. Applications under study

Considering all remote sensing methods, the most commonly studied application seems to be the automated extraction of power line components, especially conductors, from the data. Extraction of towers and poles or some small structures such as insulators has also been studied, but to a lesser extent than extraction of conductors. Methods and expected level of details in the results vary significantly depending on the data source. Considering the overall feasibility for reliable automated detection and detailed 3D reconstruction of conductors and poles, ALS and MLS point clouds may be the most promising approaches.

Inspection of faults in small components such as conductors and insulators requires detailed images taken from helicopters, UAVs or mobile mapping systems. Several studies in this field have been presented. Thermal images are used to detect hot spots indicating faults in power line components. The technique is in operational use, but the number of research articles from recent years is small. Related to component inspection, there is also interesting research aiming to develop climbing robots and various camera systems that could be used in the monitoring. Robots are able to do some surveillance and maintenance work, but further development of automated analysis is needed.

Monitoring of vegetation around power lines is generally a less common research topic than monitoring of the power line components. However, studies based on optical satellite images and aerial images from fixed-wing aircraft have mainly concentrated on vegetation. The line components themselves are not normally visible in these data sources, but the data are well suited for vegetation monitoring. Research topics in this field have included extraction of vegetation, tree species classification, tree height estimation, and determination of the position of trees with respect to power lines.

ALS data, possibly combined with aerial images, are also well suited for detailed monitoring of vegetation in power line corridors. Individual trees can be analysed and their growth can be monitored, distances between power line components and vegetation can be determined, and tree species classification has also been investigated. According to comparative studies related to power line monitoring, the accuracy of height determination for trees and poles is clearly higher from ALS than aerial images (Cai and Walker, 2010; Mills et al., 2010). In a coarser analysis of larger areas, however, other techniques can also perform well. In a recent comparison of SAR interferometry, SAR radargrammetry, satellite stereo imagery, aerial stereo imagery and ALS data for forest inventory, all these 3D methods provided reasonably good estimates for plot-level canopy height, biomass and stem volume if a DTM was available (Yu et al., 2015). It should be noted that the number of ALS studies concentrating on vegetation in power line corridors is small, but generally, vegetation mapping from ALS data has been a topic of intensive research and good results have been achieved. Basically the same approaches can be applied in power line monitoring applications. MLS data also provide interesting data for detailed vegetation mapping, although studies concentrating on power line corridors have not yet been published.

Some studies related to disaster monitoring around power lines can be found. SAR images are basically well suited for such applications due to their all-weather capability and large aerial coverage. The frequency band and resolution of the data, however, affect their feasibility. The most promising application area for SAR images is probably the detection of storm-damaged forests around power lines. Rough detection of damage in power line components can also be possible from SAR images in favourable conditions. In some cases, for example, collapsed towers could be detected, indicating damage in the surrounding area. It is, however, important to note that the visibility of objects in SAR images varies depending on viewing geometry. Due to their large flexibility, UAVs have also been suggested for applications such as damage assessments after natural disasters or other incidents (Toth and Gilpin-Jackson, 2010).

Research literature clearly concentrates on the development of automated methods for power line monitoring applications. Visual and manual inspection methods or semi-automated approaches are not often studied in articles, although they are probably still common in practical work (Pulkkinen, 2015). It is important to save costs and reduce human labour in power line monitoring, and the methods discussed in research literature provide means for that. Overall, power line companies will need several methods to inspect all power line system components and to detect vegetation encroachments and damage caused by natural disasters in corridors.

Good results for automatic algorithms are typically presented in articles. For example, accuracy levels even clearly above 90% have been reported for automated extraction of conductors from ALS and aerial image data (Jwa and Sohn, 2012; Li et al., 2010a). However, due to the large variety of study areas and quality evaluation methods, it is impossible to present general conclusions on the achievable accuracy or comparisons between different approaches. In many studies, results have only been presented with a few figures. It seems that studies with larger tests in practical conditions and numerical quality analyses are still relatively rare. This, together with the large amount of ongoing research suggests that even the most basic problems such as automatic detection of power line conductors from images and point clouds have not been fully solved and tested yet.

10.3. Selection of remote sensing methods

As summarised in Table 1, each remote sensing method has its specific advantages and challenges when considering power line corridor surveys. Basically, satellite images provide capability for continuous monitoring of large areas, which is valuable for this application. There is, however, some discrepancy between the spatial resolution desired in power line monitoring applications and the available satellite data. The most promising applications for satellite data are related to vegetation monitoring in power line corridors and surrounding areas on a coarse level, i.e. not considering individual trees. Both optical and SAR images can be applied. In particular, if a DTM of the area is available, height data derived from satellite or aerial images can be used to calculate the height of vegetation under conductors. This could also be a cost-effective solution to update DSMs and thus to monitor the growth of forest. A DTM is normally difficult to derive from satellite or aerial image data, unless the vegetation is very sparse. Information on forest measurement accuracy achievable from different data sources can be found in Yu et al. (2015).

Compared to satellite images, airborne and land-based systems provide more detailed data, but frequent covering of very large areas is not so practical. Laser scanning has developed rapidly in recent years. Dense 3D point clouds are inherently well suited for mapping of power line conductors, poles and individual trees, and they provide a good basis for automated analyses. Such point clouds can be acquired both from airborne and land-based

Table 1
Main applications, specific advantages and challenges of different remotely sensed data sources in power line corridor surveys. The column "Main applications in power line literature" is based on the contents of published research related to power lines. In "Specific advantages" and "Challenges", the general properties of the data sources are taken into account in order to consider their potential for power line monitoring.

Data source (Typical highest resolution or point density)	Main applications in power line literature	Specific advantages	Challenges
SAR images (Highest resolution ⩽ 1 m)	• Mapping of power lines and towers • Monitoring of landslides and ground subsidence • Disaster monitoring: storm damage in forests, damaged towers	• All-weather imaging capability • Frequent coverage of large areas theoretically possible with satellite images and thus good possibilities for monitoring and change detection • Can be used to create elevation models using InSAR or radargrammetry and also to measure forest tree height, if a DTM is available • Potential for vegetation mapping and monitoring using elevation changes or radar backscattering changes	• Coarse spatial resolution, speckle • Not easy to interpret (contents different from optical images) • Visibility of objects can vary a lot, depending on factors such as viewing geometry • Availability of data in a given area and time not necessarily good • Very-high-resolution data (⩽ 1 m) are costly • Moisture and roughness interfere with biomass estimates when using backscatter • In amplitude change detection, the same image acquisition geometry is required
Optical satellite images (Highest resolution 0.5–1 m)	• Vegetation monitoring	• Frequent coverage of large areas theoretically possible • Data with good visual interpretability and spatial resolution from space • Availability of multispectral data, which are well suited for classification of vegetation • Possibility for height measurements from stereo images and for forest tree height measurements, especially if a DTM is available	• Cannot be obtained in cloudy and dark conditions • Availability of data in a given area and time not necessarily good • Very-high-resolution data are costly
Optical aerial images (Highest resolution from fixed-wing aircraft 5–10 cm and from helicopters < 1 cm)	• Vegetation monitoring (from fixed-wing aircraft) • Mapping of conductors and pylons (from helicopters) • Inspection of power line components (from helicopters)	• High spatial resolution: Even < 1 cm possible from helicopters, which allows inspection of small components • Flexibility in data acquisition, especially from helicopters • Possibility for height measurements from stereo images and for forest tree height measurements, especially if a DTM is available	• Cannot be obtained through clouds or in dark conditions (however, images can be taken under cloud cover with present digital cameras) • Several factors, such as vehicle motion can affect image quality • 3D modelling of conductors is difficult from aerial images • Mapping of lower vegetation is difficult from aerial images
Thermal images (Highest resolution from aerial platforms < 5 cm)	• Fault monitoring in power line components	• Possibility to reveal faults in the network based on relative temperature differences	• Absolute temperature measurements may be difficult to carry out
ALS data (Highest point density from fixed-wing aircraft dozens of points/m^2 and from helicopters hundreds of points/m^2)	• Mapping of conductors and pylons • Mapping of individual trees near power lines	• Detailed 3D data directly available, which allows accurate modelling of power line structures and nearby trees • Not dependent on external lightning conditions • Possibility for high-quality measurement of tree height growth and for estimating future threats • Flexibility in data acquisition, especially from helicopters • Recently possible also from UAVs	• High point density required for reliable mapping of small and narrow objects • Depending on the scanning geometry, not necessarily many returns from vertical poles
Land-based mobile mapping data (Highest point density thousands of points/m^2)	• Mapping of conductors and pylons • Inspection of power line components	• Very detailed 3D data directly available by laser scanning • Detailed images can also be acquired • Panoramic imaging geometry enables accurate reconstruction of towers and poles • Possibility for high-quality estimates of vegetation • Allows assessment of tree diameters and modelling of the tree trunks	• Power lines not necessarily easy to reach with ground vehicles • Land-based mapping can be slow, especially in forests • The measurement geometry does not allow detection of components from the top
UAV data (Highest resolution of images < 1 cm and highest point density of laser scanning hundreds of points/m^2)	• Mapping of power lines and towers • Inspection of power line components • Detailed mapping of vegetation	• High flexibility in data acquisition • Lower costs compared to other aerial platforms • Potential for diverse applications • Rapid development of UAV components and battery technology is improving the feasibility for operational applications	• Developing technology (e.g., operational and regulatory issues) • Maximum flying time with current battery technology about 2 h (dependent of the platform) • Combustion engines often unsuitable because of high-amplitude vibrations

platforms (MMS). The efficiency of MMS in the mapping of power lines is naturally lower than that of airborne systems, especially in forest environments where slow platforms such as ATV or personal backpack have to be used. However, the high precision of the data allows for more detailed risk analysis of the conditions of the power line structures and surrounding vegetation.

Monitoring approaches using UAVs are clearly becoming more popular as the technology advances. UAVs are mainly an alternative to manned helicopters and airplanes, and they provide advantages such as lower costs, higher flexibility in data acquisition, and ability to fly near the power lines. The number of UAV-based studies concentrating on power line monitoring from the application point of view is still limited. Aspects related to the control and navigation of the UAVs along power lines have been given more attention. This suggests that there are still technical challenges in UAV-based monitoring. During recent years, the development of battery technology has been rapid, and the platform-dependent maximum flying time is currently about 2 h, allowing commercial applications. A sufficient power source for longer term operations is still lacking.

Table 2 summarises the most feasible remote sensing methods for three basic applications in power line monitoring, i.e., (1) mapping and inspection of power line components, (2) vegetation monitoring, and (3) disaster monitoring. Disaster monitoring can include both component and vegetation monitoring, but it is considered a special case due to its specific requirements for rapid data acquisition and analysis. The feasibility was evaluated based on power line monitoring studies referred to in this article and the specific advantages and challenges of the data sources summarised in Table 1. It represents the authors' interpretation of the material. In particular, the following aspects were considered important: visibility of features of interest in the data; flexibility of data acquisition from the application point of view; existence of previous studies demonstrating the application.

10.4. Topics for further research

Based on the above discussion, it can be expected that the best benefits from remote sensing -based monitoring could be achieved by combining different approaches in an optimal way. In research literature, however, multisource data are seldom used. The most common examples until now have concentrated on the integration of ALS data and aerial images in vegetation monitoring (e.g., Frank et al., 2010; Li et al., 2012b). Examples of further research topics in this field could include:

- Optimal integration of ALS and MLS data to achieve detailed but cost-effective 3D mapping of power lines and surrounding vegetation.
- Integration of satellite image -based monitoring of large areas and detailed mapping with airborne and land-based mobile mapping techniques, including UAVs. This could include, for example, rough detection of storm damage, thinning or clear-cut areas from satellite images and mapping of the damaged or changed areas with UAVs and MMS systems. Thinning and clear cuts around power lines can cause additional risks for the power line components because the remaining trees in these areas fall more easily than trees in a dense forest.
- Multisensoral UAV surveys for power line applications.
- Integration of standard remote sensing techniques with climbing robots and camera systems on power line structures to achieve versatile and detailed monitoring capability.

In this future development, special attention should be given to rapidly developing remote sensing techniques such as UAVs and laser scanning from airborne and land-based platforms. First studies using laser scanner data from UAVs have been carried out. With UAV laser data similar or even better performance can be achieved than with conventional helicopter ALS data. In the future, when UAV-based laser scanner data can be acquired for dozens of kilometres during the same flight, this technique will be superior to other laser scanning techniques also when considering the costs. Multisensoral UAV systems, combining laser scanning with thermal imaging and spectrometry also provide interesting possibilities for further development of power line monitoring applications.

The use of land-based systems is also an increasing trend. The increased complexity of the grid system favours data collection from the ground. Power lines next to a road network can be mapped quite efficiently and possibly with substantially lower costs using MLS than ALS (Cheng et al., 2014). In general, the costs of MMS are roughly comparable with aircraft-based ALS. Also mapping of very complex power line networks in urban environments, especially in rapidly expanding mega cities in developing countries, would be a perfect task for such approaches. MLS is not as sensitive to weather conditions as ALS and can be used, for example, to find the cause for an outage during a storm when flying is not possible (Cheng et al., 2014). MLS could also provide a convenient method to fill data gaps that may remain after a flying campaign. In addition, backpack systems can be used to collect data from areas where more detailed information is needed. Overall, mobile mapping data could be optimal data when combined with airborne data.

In the near future, multispectral laser scanning from airborne and mobile mapping sensors will open up interesting possibilities to further improve automated analysis approaches for trees and other objects. The first airborne multispectral laser scanner Optech Titan was introduced in early 2015. Preliminary results show 93.5% accuracy in tree species classification with three classes (spruce,

Table 2
The most feasible remote sensing methods for three basic power line monitoring tasks (methods are not listed in their order of importance).

Application in power line monitoring	The most feasible remote sensing data sources
Mapping and inspection of power line components	
• Mapping of conductors, poles and towers	ALS data from any platform (including UAVs); MLS data; Optical image data from helicopters, UAVs and MMS systems
• Inspection of components (e.g., detection of faults in conductors and insulators)	Optical and thermal images from helicopters, UAVs and MMS systems; climbing robots and camera systems planned for detailed monitoring of the structures
Vegetation monitoring	
• Monitoring of forest around power lines (e.g., forest growth, tree species, clear cuts)	ALS data from helicopters and fixed-wing aircraft; optical aerial images; optical satellite images
• Mapping of individual trees possibly threatening the power line	ALS data from any platform; MLS data; Optical image data from fixed-wing aircraft, helicopters, UAVs and MMS systems
Disaster monitoring	
• Rough detection of damaged areas	SAR satellite images; optical aerial images if possible
• More detailed mapping of the damage	Depending on local conditions and schedule: optical aerial images; UAV data; MMS data

pine and deciduous), and high feasibility for land cover classification (Ahokas et al., in press). Recently there have also been significant advances in the receiver technology for lidar devices. Flash lidar type focal plane array receivers enable the measurement of multiple spatially parallel echo signals (ASC, 2015). Single photon avalanche diodes (SPAD) have also been used to improve the sensitivity and measurement range of the receiver. Especially the improvement in the recovery time of the SPAD arrays has improved their applicability to multiple echo laser scanning (SigmaSpace, 2016). Generally, remote sensing technology is developing rapidly (Toth and Jóźków, 2016), and the most recent development should be taken into account when planning future research and practical monitoring applications.

In existing literature, the starting point for power line extraction is normally remotely sensed data from one date, without prior knowledge on the location of the power line structures. In many cases, however, some map data are available. They can include, for example, transmission line connections stored in topographic databases, or network information systems of power transmission and distribution companies. The map data could be used to guide the detection and modelling process or they could be used as a starting point for change detection. This topic should be studied to efficiently exploit the existing data and possibly achieve higher level of automation. This is also important from the point of view of updating the map information. In addition, it is worth noting that existing map data can be used for navigating UAVs along power lines.

Another topic that should be studied in the context of power line monitoring is change detection based on remote sensing, where datasets from two or more dates are compared to each other. This could be an effective approach to automatically detect problems in the network components or vegetation threatening the line. For example, change detection techniques with ALS data allow detection of individual, damaged trees (Yu et al., 2004).This approach is also well suited for monitoring vegetation growth, clear cuts and thinning. In addition to ALS data, any other remote sensing method discussed in this review can be exploited in change detection analyses.

11. Conclusions

A large number of studies have been published on the use of remote sensing methods in power line corridor surveys. Data sources used in the studies and discussed in this review article include SAR images, optical satellite and aerial images, thermal images, airborne laser scanner data, mobile mapping data, and UAV data. Most of the studies have concentrated on the mapping and analysis of network components. In particular, automated extraction of power line conductors has received much attention, and promising results have been achieved. For example, accuracy levels above 90% have been presented for extraction of conductors from ALS data or aerial images. However, in many studies datasets have been small and numerical quality analyses have been omitted. Mapping of vegetation around power lines has received less attention than mapping of the components, but several studies have also been carried out in this field, especially using optical aerial and satellite images. Despite the importance of disaster monitoring in power line networks, only a few research articles have concentrated on this topic.

Based on the literature review, we believe that in future research more attention should be given to the integrated use of various data sources. Each remote sensing technique has its specific advantages and challenges, and an integrated approach can benefit from the various techniques in an optimal way. Integrated approaches could include, for example, rough monitoring based on satellite data followed by detailed inspection of changed or problematic areas by using helicopters, UAVs and mobile mapping systems. Knowledge in related fields, such as vegetation monitoring from ALS, SAR and optical image data should be exploited effectively to develop useful monitoring approaches. For example, the use of ALS data for vegetation monitoring in power line corridors has been addressed only in a few studies, but ALS-based vegetation monitoring in general has been a topic of active research. The integration of existing map data with automated extraction methods should be studied. Change detection approaches based on remote sensing would also be worth studying to detect problematic points in the network and to monitor the growth of vegetation. Special attention should be given to rapidly developing remote sensing techniques such as UAVs and laser scanning from airborne and land-based platforms. It is likely that effective, flexible and highly automated monitoring methods can be developed using these techniques, allowing commercial applications.

To demonstrate and verify the capabilities of automated monitoring approaches, large tests in various environments and practical monitoring conditions are needed. These should also include difficult cases such as power lines in forests. To develop efficient integrated approaches, careful quality analyses and comparisons between different data sources, methods and individual algorithms are needed.

Acknowledgements

The authors wish to thank Heli Honkanen for her help with literature searches, Kirsi Karila for her help with a figure, Niko Vuokko for providing information on current power line inspection methods, Mikko Jalonen for providing a photograph and information on power lines in Finland and Lingli Zhu for providing a photograph. The financial support from the Academy of Finland (projects ‘Centre of Excellence in Laser Scanning Research’ (project decision number 272195), ‘Interaction of Lidar/Radar Beams with Forests Using Mini-UAV and Mobile Forest Tomography’ (259348), ‘Competence-Based Growth Through Integrated Disruptive Technologies of 3D Digitalization, Robotics, Geospatial Information and Image Processing/Computing – Point Cloud Ecosystem’ (293389), and ‘Integration of Large Multisource Point Cloud and Image Datasets for Adaptive Map Updating’ (295047)) and the European Space Agency – intergovernmental organisation (project ‘SharperSat – Maintenance and Recovery of High Voltage Electricity Transport System’) is gratefully acknowledged.

References

Aggarwal, R.K., Johns, A.T., Jayasinghe, J.A.S.B., Su, W., 2000. An overview of the condition monitoring of overhead lines. Electric Power Syst. Res. 53 (1), 15–22.

Ahmad, J., Malik, A.S., Xia, L., 2011. Vegetation monitoring for high-voltage transmission line corridors using satellite stereo images. In: Proc. 2011 National Postgraduate Conference (NPC), IEEE, Kuala Lumpur, 19–20 September, 5 p.

Ahmad, J., Malik, A.S., Xia, L., Ashikin, N., 2013. Vegetation encroachment monitoring for transmission lines right-of-ways: a survey. Electric Power Syst. Res. 95, 339–352.

Ahmad, J., Malik, A.S., Abdullah, M.F., Kamel, N., Xia, L., 2014. A novel method for vegetation encroachment monitoring of transmission lines using a single 2D camera. Pattern Anal. Appl. 18 (2), 419–440. http://dx.doi.org/10.1007/s10044-014-0391-9.

Ahokas, E., Kaartinen, H., Matikainen, L., Hyyppä, J., Hyyppä, H., 2002. Accuracy of high-pulse-rate laser scanners for digital target models. In: Proc. 21st EARSeL Symposium, Observing Our Environment from Space: New Solutions for a New Millennium. Balkema Publishers, Paris, France.

Ahokas, E., Hyyppä, J., Yu, X., Liang, X., Matikainen, L., Karila, K., Litkey, P., Kukko, A., Jaakkola, A., Kaartinen, H., Holopainen, M., Vastaranta, M., in press. Towards automatic single-sensor mapping by multispectral airborne laser scanning. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Prague, Czech Republic (in press).

Arastounia, M., Lichti, D.D., 2013. Automatic extraction of insulators from 3D LiDAR data of an electrical substation. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2 (5/W2), 19–24.

Arastounia, M., Lichti, D.D., 2015. Automatic object extraction from electrical substation point clouds. Remote Sensing 7, 15605–15629.

ASC, 2015. Advanced Scientific Concepts Inc. <http://wwwadvancedscientificconcepts.com/> (Accessed 22 April, 2016).

Ax, M., Thamke, S., Kuhnert, L., Kuhnert, K.-D., 2013. UAV based laser measurement for vegetation control at high-voltage transmission lines. Adv. Mater. Res. 614–615, 1147–1152.

Axelsson, P., 1999. Processing of laser scanner data—algorithms and applications. ISPRS J. Photogramm. Remote Sens. 54 (2–3), 138–147.

Baltsavias, E.P., 1999. A comparison between photogrammetry and laser scanning. ISPRS J. Photogramm. Remote Sens. 54 (2–3), 83–94.

Beraldin, J.-A., Blais, F., Lohr, U., 2010. Laser scanning technology. In: Vosselman, G., Maas, H.-G. (Eds.), Airborne and Terrestrial Laser Scanning. Whittles Publishing, Dunbeath, Scotland, UK, pp. 1–42.

Bernstein, R., Di Gesù, V., 1999. A combined analysis to extract objects in remote sensing images. Pattern Recogn. Lett. 20, 1407–1414.

Blazquez, C.H., 1994. Detection of problems in high-power voltage transmission and distribution lines with an infrared scanner/video system. In: Proc. SPIE 2245 (Thermosense XVI: An International Conference on Thermal Sensing and Imaging Diagnostic Applications), pp. 27–32.

Bunting, P., Lucas, R., 2006. The delineation of tree crowns in Australian mixed species forests using hyperspectral compact airborne spectrographic imager (CASI) data. Remote Sens. Environ. 101 (2), 230–248.

Cabo, C., Ordoñez, C., García-Cortés, S., Martínez, J., 2014. An algorithm for automatic detection of pole-like street furniture objects from mobile laser scanner point clouds. ISPRS J. Photogramm. Remote Sens. 87, 47–56.

Cai, J., Walker, R., 2010. Height estimation from monocular image sequences using dynamic programming with explicit occlusions. IET Comput. Vision 4 (3), 149–161.

Campoy, P., Correa, J.F., Mondragón, I., Martínez, C., Olivares, M., Mejías, L., Artieda, J., 2009. Computer vision onboard UAVs for civilian tasks. J. Intell. Rob. Syst. 54 (1–3), 105–135.

Carande, R.E., Marra, M., Cronin, D., Nagy, P., 1998. Automated mapping using airborne IFSAR data. In: Proc. 1998 IEEE International Geoscience and Remote Sensing Symposium (IGARSS '98), Seattle, WA, 6-10 July, vol. 1, pp. 360–362.

Castellucci, P.B., Lucca, L.C., Sant'Anna, M., Traballe, G., Mustacio, V.H., Resende da Silva, J.F., Vallin, S., 2013. Pole and crossarm identification in distribution power line images. In: Proc. 2013 Latin American Robotics Symposium and Competition (LARS/LARC), IEEE, Arequipa, 21-27 October, pp. 2–7.

Cheng, L., Tong, L., Wang, Y., Li, M., 2014. Extraction of urban power lines from vehicle-borne lidar data. Remote Sensing 6 (4), 3302–3320.

Clark, M.L., Roberts, D.A., Clark, D.B., 2005. Hyperspectral discrimination of tropical rain forest tree species at leaf to crown scales. Remote Sens. Environ. 96 (3–4), 375–398.

Clode, S., Rottensteiner, F., 2005. Classification of trees and powerlines from medium resolution airborne laserscanner data in urban environments. In: Proc. APRS Workshop on Digital Image Computing (WDIC 2005), Brisbane, Australia, 21 February, pp. 191–196.

Colomina, I., Molina, P., 2014. Unmanned aerial systems for photogrammetry and remote sensing: a review. ISPRS J. Photogramm. Remote Sens. 92, 79–97.

Debenest, P., Guarnieri, M., 2010. Explinερ — From prototype towards a practical robot for inspection of high-voltage lines. In: Proc. 2010 1st International Conference on Applied Robotics for the Power Industry (CARPI), IEEE, Montreal, QC, 5-7 October. http://dx.doi.org/10.1109/CARPI.2010.5624434, 6 p.

Debenest, P., Guarnieri, M., Takita, K., Fukushima, E.F., Hirose, S., Tamura, K., Kimura, A., Kubokawa, H., Iwama, N., Shiga, F., 2008. Expliner - Robot for inspection of transmission lines. In: Proc. IEEE International Conference on Robotics and Automation, 2008 (ICRA 2008), Pasadena, CA, 19-23 May, pp. 3978–3984.

Del-Cerro, J., Aguirre, I., Barrientos, A., 2001. Development of a low cost autonomous minihelicopter for power lines inspections. In: Proc. SPIE 4195 (Mobile Robots XV and Telemanipulator and Telepresence Technologies VII), 7 p.

Deng, C., Wang, S., Huang, Z., Tan, Z., Liu, J., 2014. Unmanned aerial vehicles for power line inspection: a cooperative way in platforms and communications. J. Commun. 9 (9), 687–692.

Deng, S., Li, P., Zhang, J., Yang, J., 2012. Power line detection from synthetic aperture radar imagery using coherence of co-polarisation and cross-polarisation estimated in the Hough domain. IET Radar Sonar Navig. 6 (9), 873–880.

Doubek, P., Perd'och, M., Matas, J., Šochman, J., 2008. Mobile mapping of vertical traffic infrastructure. In: Perš, Janez (Ed.), In: Proc. 13th Computer Vision Winter Workshop, Moravske Toplice, Slovenia, 4–6 February.

Dowman, I.J., Jacobsen, K., Konecny, G., Sandau, R., 2012. High resolution optical satellite imagery. Whittles Publishing.

El-Sheimy, N., 2005. An overview of mobile mapping systems. In: Proc. FIG Working Week 2005 and GSDI-8—From Pharaos to Geoinformatics, Cairo, Egypt, 16–21 April, 24 p, (on CDROM).

Elachi, C., 1987. Introduction to the Physics and Techniques of Remote Sensing. John Wiley and Sons Inc.

EPRI, 2008. Future inspection of overhead transmission lines. Report, 88 p. <http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001016921> (Accessed 26 November, 2015).

Eriksson, L.E.B., Fransson, J.E.S., Soja, M.J., Santoro, M., 2012. Backscatter signatures of wind-thrown forest in satellite SAR images. In: Proc. 2012 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) , Munich, 22–27 July, pp. 6435–6438.

Essen, H., Boehmsdorff, S., Biegel, G., Wahlen, A., 2002. On the scattering mechanism of power lines at millimeter-waves. IEEE Trans. Geosci. Remote Sens. 40 (9), 1895–1903.

Fernandes, R.A., 1989. Monitoring system for power lines and right-of-way using remotely piloted drone. Patent, US 4818990 A.

Frank, M., Pan, Z., Raber, B., Lenart, C., 2010. Vegetation management of utility corridors using high-resolution hyperspectral imaging and LiDAR. In: Proc. 2010 2nd Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing (WHISPERS) , IEEE, Reykjavik, Iceland, 14–16 June, 4 p.

Fransson, J.E.S., Walter, F., Blennow, K., Gustavsson, A., Ulander, L.M.H., 2002. Detection of storm-damaged forested areas using airborne CARABAS-II VHF SAR image data. IEEE Trans. Geosci. Remote Sens. 40 (10), 2170–2175.

Frate, J., Gagnon, D., Vilandre, R., Dansereau, R., 2000. Evaluation of overhead line and joint performance with high-definition thermography. In: Proc. 2000 IEEE ESMO - 2000 IEEE 9th International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance, Montréal, Qué, Canada, 8-12 October, pp. 145–151.

Ge, L., Chang, H.-C., Rizos, C., 2007. Mine subsidence monitoring using multi-source satellite SAR images. Photogramm. Eng. Remote Sens. 73 (3), 259–266.

Golightly, I., Jones, D., 2003. Corner detection and matching for visual tracking during power line inspection. Image Vis. Comput. 21 (9), 827–840.

Gonzalez-Aguilera, D., Del Pozo, S., Lopez, G., Rodriguez-Gonzalvez, P., 2012. From point cloud to CAD models: laser and optics geotechnology for the design of electrical substations. Opt. Laser Technol. 44 (5), 1384–1392.

Gu, I.Y.H., Sistiaga, U., Berlijn, S.M., Fahlstrom, A., 2009. Online detection of snow coverage and swing angles of electrical insulators on power transmission lines using videos. In: Proc. 2009 16th IEEE International Conference on Image Processing (ICIP) , Cairo, Egypt, 7–10 November, pp. 3249–3252.

Gu, Y., Hsu, L.-T., Kamijo, S., 2015. Passive sensor integration for vehicle self-localization in urban traffic environment. Sensors 2015 (15), 30199–30220. http://dx.doi.org/10.3390/s151229795.

Guan, H., Yu, Y., Li, J., Ji, Z., Zhang, Q., 2016. Extraction of power-transmission lines from vehicle-borne lidar data. Int. J. Remote Sens. 37 (1), 229–247.

Guo, B., Huang, X., Zhang, F., Sohn, G., 2015. Classification of airborne laser scanning data using JointBoost. ISPRS J. Photogramm. Remote Sens. 100, 71–83.

Guo, B., Li, Q., Huang, X., Wang, C., 2016. An improved method for power-line reconstruction from point cloud data. Remote Sensing 8 (36), 17.

Ha, H., Han, S., Lee, J., 2012. Fault detection on transmission lines using a microphone array and an infrared thermal imaging camera. IEEE Trans. Instrum. Meas. 61 (1), 267–275.

Haala, N., Peter, M., Kremer, J., Hunter, G., 2008. Mobile lidar mapping for 3D point cloud collection in urban areas—a performance test. Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci. 37 (B5), 1119–1124.

, . third ed.Henderson, F.M., Lewis, A.J. (Eds.), 1998. Principles & Applications of Imaging Radar, Manual of Remote Sensing third ed., vol. 2 John Wiley & Sons Inc, New York.

Hollaus, M., Mücke, W., Roncat, A., Pfeifer, N., Briese, C., 2014. Full-waveform airborne laser scanning systems and their possibilities in forest applications. In: Maltamo, M., Næsset, E., Vauhkonen, J. (Eds.), Forestry Applications of Airborne Laser Scanning, Concepts and Case Studies. Springer, Dordrecht, pp. 43–61.

Hrabar, S., Merz, T., Frousheger, D., 2010. Development of an autonomous helicopter for aerial powerline inspections. In: Proc. 2010 1st International Conference on Applied Robotics for the Power Industry (CARPI) , IEEE, Montreal, QC, 5–7 October, 6 p.

Hyyppä, J., Yu, X., Hyyppä, H., Vastaranta, M., Holopainen, M., Kukko, A., Kaartinen, H., Jaakkola, A., Vaaja, M., Koskinen, J., Alho, P., 2012. Advances in forest inventory using airborne laser scanning. Remote Sensing 4, 1190–1207.

Iasio, C., Novali, F., Corsini, A., Mulas, M., Branzanti, M., Benedetti, E., Giannico, C., Tamburini, A., Mair, V., 2012. COSMO SkyMed high frequency-high resolution monitoring of an alpine slow landslide, Corvara in Badia, Northern Italy. In: Proc. 2012 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) , Munich, 22–27 July, pp. 7577–7580.

Ishino, R., Tsutsumi, F., 2004. Detection system of damaged cables using video obtained from an aerial inspection of transmission lines. In: Proc. IEEE Power Engineering Society General Meeting, 2004, Denver, CO, 10 June, vol. 2, pp. 1857–1862.

ISPRS ICWG I/Vb, 2016. RPAS/UAV regulations – Useful links. International Society for Photogrammetry and Remote Sensing, Intercommission Working Group I/Vb, <http://www2.isprs.org/commissions/comm1/icwg15b/resources.html> (Accessed 11 April, 2016).

Ituen, I., Sohn, G., 2010. The way forward: advances in maintaining right-of-way of transmission lines. Geomatica 64 (4), 451–462.

Jaakkola, A., Hyyppä, J., Kukko, A., Yu, X., Kaartinen, H., Lehtomäki, M., Lin, Y., 2010. A low-cost multi-sensoral mobile mapping system and its feasibility for tree measurements. ISPRS J. Photogramm. Remote Sens. 65 (6), 514–522.

Jiang, J., Zhao, L., Wang, J., Liu, Y., Tang, M., Ji, Z., 2011. The electrified insulator parameter measurement for flashover based on photogrammetric method. In: Proc. SPIE 8002 (MIPPR 2011: Multispectral Image Acquisition, Processing, and Analysis), 80021l, 7 p.

Jingnan, L., 2010. Progress in deformation monitoring for dams, bridges and power lines. Annals GIS 16 (2), 81–90.

Jones, D.I., Earp, G.K., 2001. Camera sightline pointing requirements for aerial inspection of overhead power lines. Electric Power Syst. Res. 57 (2), 73–82.

Jones, D.I., Whitworth, C.C., Duller, A.W.G., 2003. Image processing methods for the visual location of power line poles. In: Morrow, P.J., Scotney, B.W. (Eds.), In: Proc. Seventh Irish Machine Vision and Image Processing Conference (IMVIP2003), Portrush, Northern Ireland, 3-5 September, pp. 177–184.

Jóźków, G., Vander Jagt, B., Toth, C., 2015. Experiments with UAS imagery for automatic modeling of power line 3D geometry. Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci. 40 (1/W4), 403–409.

Jwa, Y., Sohn, G., 2012. A piecewise catenary curve model growing for 3D power line reconstruction. Photogramm. Eng. Remote Sens. 78 (12), 1227–1240.

Kaartinen, H., Hyyppä, J., Kukko, A., Jaakkola, A., Hyyppä, H., 2012a. Benchmarking the performance of mobile laser scanning systems using a permanent test field. Sensors 12 (9), 12814–12835.

Kaartinen, H., Hyyppä, J., Yu, X., Vastaranta, M., Hyyppä, H., Kukko, A., Holopainen, M., Heipke, C., Hirschmugl, M., Morsdorf, F., Næsset, E., Pitkänen, J., Popescu, S., Solberg, S., Wolf, B.M., Wu, J.-C., 2012b. An international comparison of individual tree detection and exctraction using airborne laser scanning. Remote Sensing 4 (4), 950–974.

Kaartinen, H., Hyyppä, J., Vastaranta, M., Kukko, A., Jaakkola, A., Yu, X., Pyörälä, J., Liang, X., Liu, J., Wang, Y., Kaijaluoto, R., Melkas, T., Holopainen, M., Hyyppä, H., 2015. Accuracy of kinematic positioning using global satellite navigation systems under forest canopies. Forests 6 (9), 3218–3236.

Karila, K., Vastaranta, M., Karjalainen, M., Kaasalainen, S., 2015. Tandem-X interferometry in the prediction of forest inventory attributes in managed boreal forests. Remote Sens. Environ. 159, 259–268.

Karjalainen, M., Kankare, V., Vastaranta, M., Holopainen, M., Hyyppä, J., 2012. Prediction of plot-level forest variables using TerraSAR-X stereo SAR data. Remote Sens. Environ. 117, 338–347.

Katrašnik, J., Pernuš, F., Likar, B., 2008. New robot for power line inspection. In: Proc. 2008 IEEE Conference on Robotics, Automation and Mechatronics, Chengdu, 21-24 September, pp. 1195–1200.

Katrašnik, J., Pernuš, F., Likar, B., 2010. A survey of mobile robots for distribution power line inspection. IEEE Trans. Power Delivery 25 (1), 485–493.

Ke, Y., Quackenbush, L.J., 2011. A review of methods for automatic individual tree-crown detection and delineation from passive remote sensing. Int. J. Remote Sens. 32 (17), 4725–4747.

Kersting, A.P.B., Centeno, J.A.S., 2007. Object oriented transmission line corridors classification using lidar technology and a non-metric digital camera. Boletim de Ciências Geodésicas 13 (2), 295–315.

Kim, E., Medioni, G., 2011. Urban scene understanding from aerial and ground LIDAR data. Mach. Vis. Appl. 22 (4), 691–703.

Kim, H.B., Sohn, G., 2013. Point-based classification of power line corridor scene using random forests. Photogramm. Eng. Remote Sens. 79 (9), 821–833.

Ko, C., Remmel, T.K., Sohn, G., 2012. Mapping tree genera using discrete LiDAR and geometric tree metrics. Bosque 33 (3), 313–319.

Kobayashi, Y., Karady, G., Heydt, G., Olsen, R., 2009. The utilization of satellite images to identify trees endangering transmission lines. IEEE Trans. Power Delivery 24 (3), 1703–1709.

Kukko, A., Kaartinen, H., Hyyppä, J., Chen, Y., 2012. Multiplatform mobile laser scanning: usability and performance. Sensors 12 (9), 11712–11733.

Kukko, A., Kaartinen, H., Zanetti, M., 2015. Backpack personal laser scanning system for grain-scale topographic mapping. In: Proc. 46th Lunar and Planetary Science Conference, Abstract #2407.

Lam, J., Kusevic, K., Mrstik, P., Harrap, R., Greenspan, M., 2010. Urban scene extraction from mobile ground based lidar data. In: Proc. 5th International Symposium on 3D Data, Processing, Visualization & Transmission, Paris, France, 17–20 May, pp. 1–8.

Larrauri, J.I., Sorrosal, G., González, M., 2013. Automatic system for overhead power line inspection using an Unmanned Aerial Vehicle—RELIFO project. In: Proc. 2013 International Conference on Unmanned Aircraft Systems (ICUAS) , IEEE, Atlanta, GA, 28–31 May, pp. 244–252.

Lehtomäki, M., Jaakkola, A., Hyyppä, J., Kukko, A., Kaartinen, H., 2010. Detection of vertical pole-like objects in a road environment using vehicle-based laser scanning data. Remote Sensing 2 (3), 641–664.

Li, B., Wu, D., Cong, Y., Xia, Y., Tang, Y., 2012a. A method of insulator detection from video sequence. In: Proc. 2012 International Symposium on Information Science and Engineering (ISISE) , IEEE, Shanghai, 14–16 December, pp. 386–389.

Li, W.H., Tajbakhsh, A., Rathbone, C., Vashishtha, Y., 2010a. Image processing to automate condition assessment of overhead line components. In: Proc. 2010 1st International Conference on Applied Robotics for the Power Industry (CARPI) , IEEE, Montreal, QC, 5–7 October, 6 p.

Li, Z., Hayward, R., Zhang, J., Liu, Y., Walker, R., 2009. Towards automatic tree crown detection and delineation in spectral feature space using PCNN and morphological reconstruction. In: Proc. 2009 16th IEEE International Conference on Image Processing (ICIP) , Cairo, Egypt, 7–10 November, pp. 1705–1708.

Li, Z., Liu, Y., Walker, R., Hayward, R., Zhang, J., 2010b. Towards automatic power line detection for a UAV surveillance system using pulse coupled neural filter and an improved Hough transform. Mach. Vis. Appl. 21 (5), 677–686.

Li, Z., Hayward, R., Liu, Y., Walker, R., 2011a. Spectral–texture feature extraction using statistical moments with application to object-based vegetation species classification. Int. J. Image Data Fusion 2 (4), 347–361.

Li, Z., Hayward, R., Walker, R., Liu, Y., 2011b. A biologically inspired object spectral-texture descriptor and its application to vegetation classification in power-line corridors. IEEE Geosci. Remote Sens. Lett. 8 (4), 631–635.

Li, Z., Bruggemann, T.S., Ford, J.J., Mejias, L., Liu, Y., 2012b. Toward automated power line corridor monitoring using advanced aircraft control and multisource feature fusion. J. Field Robotics 29 (1), 4–24.

Liang, X., Hyyppä, J., Kukko, A., Kaartinen, H., Jaakkola, A., Yu, X., 2014a. The use of a mobile laser scanning system for mapping large forest plots. IEEE Geosci. Remote Sens. Lett. 11 (9), 1504–1508.

Liang, X., Kukko, A., Kaartinen, H., Hyyppä, J., Yu, X., Jaakkola, A., Wang, Y., 2014b. Possibilities of a personal laser scanning system for forest mapping and ecosystem services. Sensors 14 (1), 1228–1248.

Liao, S., An, J., 2015. A robust insulator detection algorithm based on local features and spatial orders for aerial images. IEEE Geosci. Remote Sens. Lett. 12 (5), 963–967.

Lin, Y., Hong, W., Tan, W., Wang, Y., Xiang, M., 2012. Airborne circular SAR imaging: Results at P-band. In: Proc. 2012 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) , Munich, 22–27 July, pp. 5594–5597.

Liu, Y., Li, Z., Hayward, R., Walker, R., Jin, H., 2009. Classification of airborne LIDAR intensity data using statistical analysis and Hough transform with application to power line corridors. In: Proc. Digital Image Computing: Techniques and Applications (DICTA '09) , IEEE, Melbourne, VIC, 1–3 December, pp. 462–467.

Lu, M.L., Kieloch, Z., 2008. Accuracy of transmission line modeling based on aerial LiDAR survey. IEEE Trans. Power Delivery 23 (3), 1655–1663.

Luo, Q., Perissin, D., Lin, H., Zhang, Y., Wang, W., 2014. Subsidence monitoring of Tianjin suburbs by TerraSAR-X persistent scatterers interferometry. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 7 (5), 1642–1650.

Luque-Vega, L.F., Castillo-Toledo, B., Loukianov, A., Gonzalez-Jimenez, L.E., 2014. Power line inspection via an unmanned aerial system based on the quadrotor helicopter. In: Proc. 2014 17th IEEE Mediterranean Electrotechnical Conference (MELECON) , Beirut, 13–16 April, pp. 393–397.

Martinez, C., Sampedro, C., Chauhan, A., Campoy, P., 2014. Towards autonomous detection and tracking of electric towers for aerial power line inspection. In: Proc. 2014 International Conference on Unmanned Aircraft Systems (ICUAS) , IEEE, Orlando, FL, 27–30 May, pp. 284–295.

Massonnet, D., Feigl, K.L., 1998. Radar interferometry and its application to changes in the Earth's surface. Rev. Geophys. 36 (4), 441–500.

McLaughlin, R.A., 2006. Extracting transmission lines from airborne LIDAR data. IEEE Geosci. Remote Sens. Lett. 3 (2), 222–226.

Melzer, T., Briese, C., 2004. Extraction and modeling of power lines from ALS point clouds. In: Proc. 28th Workshop of the Austrian Association for Pattern Recognition, Hagenberg, Austria, pp. 47–54.

Mills, S.J., Castro, M.P.G., Li, Z., Cai, J., Hayward, R., Mejias, L., Walker, R.A., 2010. Evaluation of aerial remote sensing techniques for vegetation management in power-line corridors. IEEE Trans. Geosci. Remote Sens. 48 (9), 3379–3390.

Mirallès, F., Pouliot, N., Montambault, S., 2014. State-of-the-art review of computer vision for the management of power transmission lines. In: Proc. 2014 3rd International Conference on Applied Robotics for the Power Industry (CARPI) , IEEE, Foz do Iguassu, 14–16 October, 6 p.

Moeller, M.S., 2006. Monitoring powerline corridors with stereo satellite imagery. In: Proc. MAPPS/ASPRS Conference, San Antonio, Texas, 6 p.

Montambault, S., Pouliot, N., 2003. The HQ LineROVer: contributing to innovation in transmission line maintenance. In: Proc. 2003 IEEE ESMO, 2003 IEEE 10th International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance, pp. 33–40.

Montambault, S., Pouliot, N., 2006. LineScout technology: Development of an inspection robot capable of clearing obstacles while operating on a live line. In: Proc. ESMO 2006, IEEE 11th International Conference on Transmission & Distribution Construction, Operation and Live-Line Maintenance, Albuquerque, NM, 15-19 October. http://dx.doi.org/10.1109/TDCLLM.2006.340744.

Montambault, S., Beaudry, J., Toussaint, K., Pouliot, N., 2010. On the application of VTOL UAVs to the inspection of power utility assets. In: Proc. 2010 1st International Conference on Applied Robotics for the Power Industry (CARPI) , IEEE, Montreal, QC, 5–7 October, 7 p.

Mu, C., Yan, Q., Feng, Y., Cai, J., Yu, J., 2009. Overview of powerlines extraction and surveillance using remote sensing technology. In: Proc. SPIE 7498 (MIPPR 2009: Remote Sensing and GIS Data Processing and Other Applications), 74981M, 8 p.

Murthy, V.S., Gupta, S., Mohanta, D.K., 2011. Digital image processing approach using combined wavelet hidden markov model for well-being analysis of insulators. IET Image In: Proc. 5 (2), 171–183.

Ninedorf, D.A., Stolper, R., Hart, J., 2008. High-voltage electrical survey advances using UV/IR. In: Proc. SPIE 6939 (Thermosense XXX), 69390K.

Oberweger, M., Wendel, A., Bischof, H., 2014. Visual recognition and fault detection for power line insulators. In: Kúkelová, Z., Heller, J. (Eds.), In: Proc. 19th Computer Vision Winter Workshop (CVWW), Křtiny, Czech Republic, 3–5 February, pp. 81–88.

Otcenasova, A., Hoger, M., Altus, J., 2014. Possible use of airborne LiDAR for monitoring of power lines in Slovak Republic. In: Proc. 2014 15th International Scientific Conference on Electric Power Engineering (EPE) , IEEE, Brno, 12–14 May, pp. 477–481.

Petrie, G., 2010. An introduction to the technology, mobile mapping systems. Geoinformatics 13 (1), 32–43.

Puente, I., González-Jorge, H., Arias, P., Armesto, J., 2011. Land-based mobile laser scanning systems: a review. Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci. 38 (5/W12), 163–168.

Pulkkinen, J., 2015. Laserkeilauksen soveltaminen sähköverkon kunnossapidossa (Laser scanning in electricity network maintenance) Master's thesis, Aalto University School of Engineering (in Finnish, English abstract).

Puttonen, E., Jaakkola, A., Litkey, P., Hyyppä, J., 2011. Tree classification with fused mobile laser scanning and hyperspectral data. Sensors 11 (5), 5158–5182.

Qin, L., Chen, S., Gao, Q., Yi, X., 2000. Inspection for electric power systems using uncooled infrared camera. In: Proc. 25th International Conference on Infrared and Millimeter Waves, 2000, Conference Digest, pp. 441–442.

Raggam, H., Franke, M., Ofner, M., Gutjahr, K., 2005. Accuracy assessment of vegetation height mapping using spaceborne IKONOS as well as aerial UltraCam stereo images. In: Proc. EARSel Workshop, 3D Remote Sensing Systems, Porto, Portugal, 10–11 June.

Reddy, M.J.B., Chandra, K.B., Mohanta, D.K., 2013. Condition monitoring of 11 kV distribution system insulators incorporating complex imagery using combined DOST-SVM approach. IEEE Trans. Dielectr. Electr. Insul. 20 (2), 664–674.

Reed, M.D., Landry, C.E., Werther, K.C., 1996. The application of air and ground based laser mapping systems to transmission line corridor surveys. In: Proc. IEEE Position Location and Navigation Symposium, Atlanta, GA, USA, 22-26 April, pp. 444–451.

Rosen, P.A., Hensley, S., Joughin, I.R., Li, F.K., Madsen, S.N., Rodriguez, E., Goldstein, R.M., 2000. Synthetic aperture radar interferometry. Proc. IEEE 88 (3), 333–382.

Sampedro, C., Martinez, C., Chauhan, A., Campoy, P., 2014. A supervised approach to electric tower detection and classification for power line inspection. In: Proc. 2014 International Joint Conference on Neural Networks (IJCNN), IEEE, Beijing, China, 6–11 July, pp. 1970–1977.

Sarabandi, K., Park, M., 1999. Millimeter-wave radar phenomenology of power lines and a polarimetric detection algorithm. IEEE Trans. Antennas Propag. 47 (12), 1807–1813.

Sarabandi, K., Park, M., 2000. Extraction of power line maps from millimeter-wave polarimetric SAR images. IEEE Trans. Antennas Propag. 48 (12), 1802–1809.

Sarabandi, K., Pierce, L., Oh, Y., Ulaby, F.T., 1994. Power lines: Radar measurements and detection algorithm for polarimetric SAR images. IEEE Trans. Aerosp. Electron. Syst. 30 (2), 632–643.

Schwarz, G., Soccorsi, M., Chaabouni-Chouayakh, H., Espinoza, D., Cerra, D., Rodriguez, F., Datcu, M., 2009. Automated information extraction from high resolution SAR images: TerraSAR-X interpretation applications. In: Proc. 2009 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2009), Cape Town, 12-17 July, vol. 4, pp. 677–680.

Sha, L., Tao, L., Mingzhou, W., Ailing, H., Wenhao, W., Kan, X., Yan, L., 2014. Study on extra-high voltage power line scatterers in time series SAR. In: Proc. 2014 3rd International Workshop on Earth Observation and Remote Sensing Applications (EORSA) , IEEE, Changsha, 11–14 June, pp. 47–51.

Sharma, H., Bhujade, R., Adithya, V., Balamuralidhar, P., 2014. Vision-based detection of power distribution lines in complex remote surroundings. In: Proc. 2014 IEEE Twentieth National Conference on Communications (NCC), Kanpur, 28 February – 2 March, 6 p.

SigmaSpace, 2016. Single photon lidar, SigmaSpace Corporation <http://www.sigmaspace.com/single-photon-lidar> (Accessed 22 April, 2016).

Sohn, G., Jwa, Y., Kim, H.B., 2012. Automatic powerline scene classification and reconstruction using airborne lidar data. ISPRS Ann. Photogramm., Remote Sens. Spatial Inf. Sci. I (3), 167–172.

Solberg, S., Astrup, R., Breidenbach, J., Nilsen, B., Weydahl, D., 2013. Monitoring spruce volume and biomass with InSAR data from TanDEM-X. Remote Sens. Environ. 139, 60–67.

Sonka, M., Hlavac, V., Boyle, R., 2008. Image Processing, Analysis, and Machine Vision, third ed. Thomson.

Stockton, G.R., Tache, A., 2006. Advances in applications for aerial infrared thermography. In: Proc. SPIE 6205 (Thermosense XXVIII), 62050C. http://dx.doi.org/10.1117/12.669513.

Sun, C., Jones, R., Talbot, H., Wu, X., Cheong, K., Beare, R., Buckley, M., Berman, M., 2006. Measuring the distance of vegetation from powerlines using stereo vision. ISPRS J. Photogramm. Remote Sens. 60 (4), 269–283.

Tang, L., Fang, L., Wang, H., 2004. Development of an inspection robot control system for 500KV extra-high voltage power transmission lines. In: Proc. SICE 2004 Annual Conference, Sapporo, 4-6 August, vol. 2, pp. 1819–1824.

Thiele, A., Boldt, M., Hinz, S., 2012. Automated detection of storm damage in forest areas by analyzing TerraSAR-X data. In: Proc. 2012 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Munich, 22–27 July, pp. 1672–1675.

Tilawat, J., Theera-Umpon, N., Auephanwiriyakul, S., 2010. Automatic detection of electricity pylons in aerial video sequences. In: Proc. 2010 International Conference on Electronics and Information Engineering (ICEIE), IEEE, Kyoto, Japan, 1-3 August, vol. 1, pp. 342–346.

Tong, W., Li, B., Yuan, J.-S., Zhao, S., 2009. Transmission line extraction and recognition from natural complex background. In: Proc. 2009 International Conference on Machine Learning and Cybernetics, IEEE, Baoding, China, 12–15 July, vol. 4, pp. 2473–2477.

Toth, C., Jóźków, G., 2016. Remote sensing platforms and sensors: a survey. ISPRS J. Photogramm. Remote Sens. 115, 22–36.

Toth, J., Gilpin-Jackson, A., 2010. Smart view for a smart grid—Unmanned Aerial Vehicles for transmission lines. In: Proc. 2010 1st International Conference on Applied Robotics for the Power Industry (CARPI), IEEE, Montreal, QC, 5–7 October, 6 p.

Ulander, L.M.H., Smith, G., Eriksson, L., Folkesson, K., Fransson, J.E.S., Gustavsson, A., Hallberg, B., Joyce, S., Magnusson, M., Olsson, H., Persson, A., Walter, F., 2005. Mapping of wind-thrown forests in southern Sweden using space- and airborne SAR. In: Proc. 2005 IEEE International Geoscience and Remote Sensing Symposium (IGARSS '05), vol. 5, pp. 3619–3622.

Ussyshkin, R.V., Theriault, L., Sitar, M., Kou, T., 2011. Advantages of airborne lidar technology in power line asset management. In: Proc. 2011 International Workshop on Multi-Platform/Multi-Sensor Remote Sensing and Mapping (M2RSM), IEEE, Xiamen, 10–12 January, 5 p.

Vasquez-Arnez, R.L., Jardini, M.G.M., Masuda, M., Carita Jr., L.A., Jardini, J.A., 2010. Preventive inspection of line insulators through corona emission: A case study. In: Proc. 2010 IEEE PES Transmission and Distribution Conference and Exposition, New Orleans, LA, USA, 19–22 April, 6 p.

Wallace, L.O., 2014. The Development and Application of a Unmanned Aerial Vehicle Laser Scanning System for Forest Management Doctoral thesis, University of Tasmania http://eprints.utas.edu.au/18720/2/Whole-Wallace-thesis.pdf (Accessed 30 November, 2015).

Whitworth, C.C., Duller, A.W.G., Jones, D.I., Earp, G.K., 2001. Aerial video inspection of overhead power lines. Power Eng. J. 15 (1), 25–32.

Woods, D., Folley, C., Kwan, Y.-T., Houshmand, B., 2004. Automatic extraction of vertical obstruction information from interferometric SAR elevation data. In: Proc. 2004 IEEE International Geoscience and Remote Sensing Symposium (IGARSS '04), vol. 6, pp. 3938–3941.

Wu, Q., An, J., 2014. An active contour model based on texture distribution for extracting inhomogeneous insulators from aerial images. IEEE Trans. Geosci. Remote Sens. 52 (6), 3613–3626.

Wu, Q., An, J., Yang, R., 2010. Extraction of power lines from aerial images based on Hough transform. In: Proc. SPIE 7862 (Earth Observing Missions and Sensors: Development, Implementation, and Characterization), 78620Q.

Wu, Q., An, J., Lin, B., 2012. A texture segmentation algorithm based on PCA and global minimization active contour model for aerial insulator images. IEEE J. Selected Topics Appl. Earth Observ. Remote Sens. 5 (5), 1509–1518.

Xie, L., Zhang, H., Wang, C., Zhang, B., Wu, F., 2014. High-voltage transmission towers detection using hybrid polarimetric SAR data. In: Proc. 2014 3rd International Workshop on Earth Observation and Remote Sensing Applications (EORSA) , IEEE, Changsha, 11–14 June, pp. 353–356.

Yan, G., Li, C., Zhou, G., Zhang, W., Li, X., 2007a. Automatic extraction of power lines from aerial images. IEEE Geosci. Remote Sens. Lett. 4 (3), 387–391.

Yan, G., Wang, J., Liu, Q., Su, L., Wang, P., Liu, J., Zhang, W., Xiao, Z., 2007b. An airborne multi-angle power line inspection system. In: Proc. IEEE International Geoscience and Remote Sensing Symposium, 2007 (IGARSS 2007), Barcelona, Spain, 23-28 July, pp. 2913–2915.

Yan, L., Wu, W., Li, T., 2011. Power transmission tower monitoring technology based on TerraSAR-X products. In: Proc. SPIE 8286 (International Symposium on Lidar and Radar Mapping 2011: Technologies and Applications), 82861E, 7 p.

Yan, L., Ailing, H., Sha, L., Xingkai, L., Wenhao, W., Tao, L., 2012. High voltage power line scattering feature analysis in multi SAR sensors and dual polarization. In: Proc. 2012 Second International Workshop on Earth Observation and Remote Sensing Applications (EORSA) , IEEE, Shanghai, China, 8–11 June, pp. 225–229.

Yang, B., Wei, Z., Li, Q., Li, J., 2012. Automated extraction of street-scene objects from mobile lidar point clouds. Int. J. Remote Sens. 33 (18), 5839–5861.

Yang, B., Dong, Z., Zhao, G., Dai, W., 2015. Hierarchical extraction of urban objects from mobile laser scanning data. ISPRS J. Photogramm. Remote Sens. 99, 45–57.

Yang, W., Zhang, H., Chen, J., Sun, H., 2007. Automatic detection of power transmission series in full polarimetric SAR imagery. In: Proc. 2007 IEEE Radar Conference, Boston, MA, 17–20 April, pp. 789–793.

Ye, F., Li, F., Hu, S., 2013. Automatic extraction of power lines by particle filtering from aerial images. In: Proc. SPIE 9069 (Fifth International Conference on Graphic and Image Processing, ICGIP 2013), 90691M.

Yu, C., Peng, Q., 2010. Icing detection using image-based 3d shape recovery. Comput.-Aided Des. Appl. 7 (3), 335–347.

Yu, X., Hyyppä, J., Kaartinen, H., Maltamo, M., 2004. Automatic detection of harvested trees and determination of forest growth using airborne laser scanning. Remote Sens. Environ. 90 (4), 451–462.

Yu, X., Hyyppä, J., Kaartinen, H., Hyyppä, H., Maltamo, M., Rönnholm, P., 2005. Measuring the growth of individual trees using multi-temporal airborne laser scanning point clouds. Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci. XXXVI (3/W19), 204–208.

Yu, X., Hyyppä, J., Karjalainen, M., Nurminen, K., Karila, K., Vastaranta, M., Kankare, V., Kaartinen, H., Holopainen, M., Honkavaara, E., Kukko, A., Jaakkola, A., Liang, X., Wang, Y., Hyyppä, H., Katoh, M., 2015. Comparison of laser and stereo optical, SAR and InSAR point clouds from air- and space-borne sources in the retrieval of forest inventory attributes. Remote Sensing 7, 15933–15954.

Zhang, J., Huang, G., Liu, J., 2010. SAR remote sensing monitoring of the Yushu earthquake disaster situation and the information service system. J. Remote Sens. 14 (5), 1038–1045.

Zhang, W., Yan, G., Wang, N., Li, Q., Zhao, W., 2007. Automatic 3D power line reconstruction of multi-angular imaging power line inspection system. In: Proc. SPIE 6752 (Geoinformatics 2007: Remotely Sensed Data and Information), 67521P.

Zheng, L., Yi, R., 2009. Fault diagnosis system for the inspection robot in power transmission lines maintenance. In: Proc. SPIE 7513 (2009 International Conference on Optical Instruments and Technology: Optoelectronic Imaging and Process Technology), 75130E.

Zhong, Y., Zuo, Q., Zhou, Y., Zhang, C., 2013. A new image-based algorithm for icing detection and icing thickness estimation for transmission lines. In: Proc. 2013 IEEE International Conference on Multimedia and Expo Workshops (ICMEW) , San Jose, CA, 15–19 July, 6 p.

Zhu, L., Hyyppä, J., 2014. Fully-automated power line extraction from airborne laser scanning point clouds in forest areas. Remote Sensing 6 (11), 11267–11282.