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Wind adaptive modeling of transmission lines using minimum description length

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ABSTRACT

The transmission lines are moving objects, which positions are dynamically affected by wind-induced conductor motion while they are acquired by airborne laser scanners. This wind effect results in a noisy distribution of laser points, which often hinders accurate representation of transmission lines and thus, leads to various types of modeling errors. This paper presents a new method for complete 3D transmission line model reconstruction in the framework of inner and across span analysis. The highlighted fact is that the proposed method is capable of indirectly estimating noise scales, which corrupts the quality of laser observations affected by different wind speeds through a linear regression analysis. In the inner span analysis, individual transmission line models of each span are evaluated based on the Minimum Description Length theory and erroneous transmission line segments are subsequently replaced by precise transmission line models with wind-adaptive noise scale estimated. In the subsequent step of across span analysis, detecting the precise start and end positions of the transmission line models, known as the Point of Attachment, is the key issue for correcting partial modeling errors, as well as refining transmission line models. Finally, the geometric and topological completion of transmission line models are achieved over the entire network. A performance evaluation was conducted over 138.5 km long corridor data. In a modest wind condition, the results demonstrates that the proposed method can improve the accuracy of non-wind-adaptive initial models on an average of 48% success rate to produce complete transmission line models in the range between 85% and 99.5% with the positional accuracy of 9.55 cm transmission line models and 28 cm Point of Attachment in the root-mean-square error.

1. Introduction

A transmission line (TL) corridor, also known as Right-of-Way (ROW), is vulnerable to potential hazards which result in unforeseen power interruptions, leading to both short and long-term power outages (Strmiska, 2000; Neal, 2009). The damage to TL components can be caused by various factors, including wind vibration (Diana et al., 2005), the corona effect (Zhao et al., 1996), corrosion (Smith and Hall, 2011), icing (Ma et al., 2011) and other environmental changes (e.g., ambient temperature, earthquakes, lightning, contamination-related flashovers). Moreover, as TL structures wear out over time, inelastic deformations occur, which cause spatial displacements of the TL components (Ituen and Sohn, 2010). In addition to these causes, vegetation is also considered as one of the most hazardous factors because it may come into contact with overhead TLs by growing in and falling down within and outside the ROW. This interference has contributed to over 30% of service interruptions, which corresponds to an economic loss of approximately $40 billion a year in the United States (Goodfellow and Peterson, 2011).

Thus, it is clear that vegetation maintenance is of critical importance in achieving utility system reliability. To accomplish this goal, maintenance practices should focus on predictive rather than reactive measures; this requires the development of systematic risk assessment and mitigation procedures. For implementing such a predictive approach, accurate detection and parameterization of all TLs in 3D are critical. For example, the necessary clearance quantity derived by vegetation encroachments can be easily determined by simulating a conductor blowout based on its maximum designed sag and swing position using parameterized TL models. This simulation-based vegetation studies can provide the advantage of being able to consider the movement of conductors and vegetation caused by varying degrees of wind speed. These models are also useful in predictive thermal ratings by precisely estimating TL sag positions (Rahim et al., 2010). However, current labor-

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centric inspection methods are inefficient in terms of time, accuracy, and cost for generating 3D TL models with high accuracy, and are insufficient to uphold such regular maintenance. In fact, utility corridor maintenance comes at a high cost; U.S. electric utility companies spent $3 billion in 2010 on vegetation management services alone (Goodfellow and Peterson, 2011). Therefore, developing a more efficient remote sensing technology for automatically reconstructing 3D TL models, which enables predictive risk analysis of utility corridors with high accuracy is urgently required (Ituen and Sohn, 2010).

1.1. Previous research works

For the last decade, a range of different techniques have been proposed by many researchers for automatically detecting and modeling TL objects, mainly using imagery or Airborne Laser Scanning (ALS) data acquired from various types of mobile platforms (e.g., ground, airborne and spaceborne sensors). In the image-based approaches, several key characteristics of TL objects were often used as *a priori* information for detecting TL objects. Yan et al. (2007) and Yang et al. (2012) proposed key features to detect TL such as its uniform brightness, straight line properties and parallel configuration among conductors in a span. However, the image-driven regularities discriminating TL from the other objects might be problematic to be generalized due to variance in background objects, light conditions and noises caused by shadows and occlusions. As a consequence, the image-based techniques often produce noisy results. To overcome this limitation, Sun et al. (2006) focused on identifying pylon structures instead of TL, such as poles and cross arms, based on stereo vision techniques and then modeling TLs between consecutive poles as a catenary curve. Hofter et al. (2013) generated 3D line models representing pylons using image sequences by proposing possible 3D locations of the endpoints of 2D line segments as random variables using epipolar constraints and generating optimal 3D lines based on maximizing the gradient similarity across neighboring views. On the other hand, Tong et al. (2009) first applied some image processing techniques, including the Marr-Hildreth edge detecting algorithm, to enhance edges by adopting a Laplacian convolution filter for extracting TL line segments. Hough Transform (HT) has also been widely used to extract a linear feature from noisy images (Tong et al., 2009; Wu et al., 2010; Zhang et al., 2010). However, due to the existence of a number of erroneous linear features on the background, a validation process to identify outliers is additionally required. For address this problem, various approaches including morphological analysis and nearest neighborhood were used to distinguish TL segments from background objects. Yan et al. (2007) proposed a Kalman filtering technology to connect fragmented TL segments detected by Radon transformation and a rule-based grouping process. Oberweger et al. (2014) presented a supervised learning method to detect TL insulator by discriminatively training of local gradient-based circular descriptors. They also proposed an automatic insulator fault analysis by extracting the individual insulator caps and check their faults by a descriptor with elliptical spatial support.

As an alternative to the optical imagery, 3D ALS point cloud has become one of primary information sources used for TL corridor mapping and risk mitigation planning. As well discussed in many researchers (Mu et al., 2009; Ko et al., 2012; Pfeifer et al., 2014; Matikainen et al., 2016), ALS data offers unique benefits to compensate the limitations of the image-based techniques by providing highly dense point clouds for mapping TLs with multiple echoes and intensity information. For the last decade, a variety of approaches have been introduced for classifying TL points and the subsequent modeling (Matikainen et al., 2016). Similar to the image-based approach, different types of *a priori* knowledges characterizing TL have been adopted for classifying TL points from ALS data which include the presence of multiple echoes over TLs, orthogonal distance between TLs themselves, or TLs and other objects, and TL structure types with respect to power voltage (Axelsson, 1999; Vale and Gomes-Mota, 2007; Liang et al., 2011). However, due to the irregular distribution of TL points, using the proposed approaches is limited in the global perspective. To compensate for the limitations, a probabilistic prediction of TL class label is frequently adopted, for example, based on Dempster-Shafer theory (Clode and Rottensteiner, 2005) and supervised classification using Random Forest classifier (Kim and Sohn, 2013) and JointBoost classifier (Guo et al., 2014). So far, those probabilistic paradigms are considered an appropriate classification method due to their high classification rate of greater than 90%. However, those techniques are still sensitive to the TL scene diversity, resulting in noisy results, producing fragmented line models or erroneously merging adjacent lines. Once the task of TL classification is completed, the reconstruction of TL models is subsequently performed based on various techniques for grouping TL points into individual lines and fitting them to a standard catenary model. These model reconstruction methods include minimum linkage hierarchical clustering and RANSAC (Melzer and Briese, 2004), catenary curve embedded local affine modeling (McLaughlin, 2006), Eigen-analysis of point distribution tensor (Ritter and Benger, 2012), piecewise model growing (PMG) (Jwa and Sohn, 2012), voxel-based hierarchical method (Cheng et al., 2014) and Markov Random Field (MRF) (Sohn et al., 2012). However, despite the number of trials to the completion of TL modeling, its success rates frequently decrease because the TL points are corrupted by undesired factors such as missing laser points causing data gaps or wind-induced conductor motions.

Recently, ALS has been rapidly adopted as a primary remote sensing technology for utility risk management. The previous research works have established solid groundwork for modeling TLs from ALS point clouds. However, most of existing works did not pay attention to negative impact of non-steady-state variable such as wind that dynamically affects position of TLs. This research considers wind blowing and the consequent effects in corridor environments. A primary motivation of this study is to propose a regression analysis for indirectly estimating the degree of wind-induced conductor motion and make TL modeling method adaptive to wind speed at difference scales. This wind-adaptive modeling approach is developed based on the Minimum Description Length (MDL) theory, which progressively rectifies modeling errors in the inner and across span domain. This paper is organized into five sections as follows: Following this introduction, Section 2 describes wind blowing effect on TLs. Section 3 presents a new method of wind-adaptive TL model reconstruction. The results and the quality assessment are discussed in Section 4. Finally, the paper presents the conclusions and suggestions of future research directions in Section 5.

2. Wind blowing effects on TL modeling

The shape of a TL can be reasonably approximated with the standard catenary curve model (McLaughlin, 2006; Jwa and Sohn, 2012). The general theory of transmission line design and maintenance is well developed based on the approximate catenary, which enables adequate calculations of the customary sag-tension and vegetation encroachment (Sugden, 1994). The problem of TL model reconstruction is to search for a member of the unknown catenaries that best-fit the TL points and determine the parameters of the standard catenary models. Recently, the state-of-the art methods claimed that the catenary reconstruction task using ALS data can be achievable with high success rates. For instances, Jwa and