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NAMED AFTER K.I. SATBAYEV

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**«Improving the methodology of 3D reconstruction of overhead power
transmission pylons based on geospatial data»**

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ANNOTATION

for the dissertation submitted in fulfillment of the requirements
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INTRODUCTION

Relevance of the Dissertation Topic. Ensuring the uninterrupted and reliable operation of the energy infrastructure is a cornerstone of national security and the socio-economic development of any country. In this context, timely monitoring of the technical condition of overhead power transmission lines (PTL) and the prevention of malfunctions represent one of the most important tasks.

Currently, PTL supports in various regions of Kazakhstan cover vast geographic territories, requiring significant resource and time expenditures for manual inspection and maintenance. In addition, complex terrain, natural obstacles, and climatic conditions reduce the efficiency of traditional monitoring methods.

The development of modern digital geoinformation technologies (LiDAR, photogrammetry, UAV surveys, satellite observation, etc.) provides a new level of solutions to these challenges. In particular, the capability of 3D modeling of supports based on point clouds, automatic recognition of their structural components, and monitoring enables optimization of contemporary processes of technical maintenance and repair.

The relevance of this research direction is further emphasized by the following factors:

- the wide distribution and structural diversity of PTL systems across Kazakhstan;
- limitations of manual inspection and shortage of skilled personnel;
- physical deterioration of PTL components and their exposure to climatic conditions;
- the need for automated processing of supports with complex geometric structures;
- increasing requirements for remote management of energy facilities within the framework of digitalization and the “Digital Kazakhstan” program.

Therefore, the development and implementation of automated 3D modeling methods that ensure accurate and reliable reconstruction of support structures represent a research area of both scientific and high industrial-practical significance.

The aim of the dissertation is to improve the methodology for 3D reconstruction of overhead power line supports based on geospatial data.

Main Problems Addressed in the Dissertation:

- comprehensive analysis of the development of monitoring methods for the condition of overhead power transmission lines and their reconstruction techniques;
- assessment of the accuracy of linear correspondence during the reconstruction of electrical networks;
- proposal of methods for redirection and segmentation of PTL supports;
- substantiation of power line structure reconstruction through determination and calculation of topological relationships between corner points.

Research Methodology. To achieve the stated objectives, system analysis, design methods, and comprehensive research approaches were applied using standard software tools.

Scientific Provisions Submitted for Defense: A component-based algorithm, which divides PTL supports into lower (inverted triangle), middle (rectangular), and upper or lateral (complex) structures, enables separate analysis of the support components and accurate determination of their segmentation positions.

The integration of 2D alpha-shape algorithms and the Random Sample Consensus (RANSAC) method allows for precise and efficient 3D reconstruction of support coordinates by modeling their internal and external structure and determining topological relationships between angular points.

Scientific Novelty of the Research Results

- A segmentation method based on a component algorithm is proposed, corresponding to the geometric features of PTL supports (lower, middle, and upper parts).
- An effective combination of 2D alpha-shapes and the RANSAC algorithm is introduced for reconstructing PTL supports, allowing for modeling of internal and external structures and determination of topological relationships between angular points through computation of their 3D coordinates.

Validity and Reliability of the Scientific Results

The validity and reliability of the obtained results and conclusions are confirmed by:

- selection of appropriate methods and models based on analysis of scientific literature, previous research, and international experience, taking into account the structural and geometric characteristics of PTL supports;
- integrated application of component segmentation, 2D alpha-shape algorithms, RANSAC, and topological analysis methods;
- testing of the proposed algorithms on point clouds and visual data from real overhead power lines, confirming their practical significance and effectiveness;
- comparison of the obtained results with traditional and alternative methods, demonstrating advantages in modeling accuracy, reconstruction time, and automation level.

Thus, the conclusions of the dissertation are scientifically substantiated, methodologically developed, and applicable in practice.

Practical Significance

The results of the dissertation are applied in the educational process of the Kazakh National Research Technical University named after K.I. Satbayev and in the implementation of industrial projects.

The main research results were obtained in the Scientific Research Laboratory of Digital and Computer Modeling of Ore Extraction Technologies from Blocks of Various Structural Complexity, which operates within the Innovation and Engineering Center of the Mining and Metallurgical Institute. The work was carried out under the Targeted Program BR21881939 titled

“Development of Resource-Saving Energy-Generating Technologies for the Mining and Metallurgical Complex and Establishment of an Innovation Engineering Center”

Approbation of the Work

The main provisions and results of the dissertation were presented and discussed at the following conferences:

- International Scientific and Technical Conference “*Satpayev Readings*” — “*Innovative Technologies: The Key to Solving Fundamental and Applied Problems in the Mining and Oil and Gas Industries of the Republic of Kazakhstan*” (Almaty, 2019);

- International Scientific and Practical Conference “*Innovative Technologies in Geospatial Digital Engineering*” dedicated to the 115th anniversary of Corresponding Member of the Academy of Sciences of the Kazakh SSR A.Zh. Mashanov and the 100th anniversary of Academician Zh.S. Erzhanov (Almaty, 2022);

- International Scientific and Technical Conference “*Actual Questions and Innovations in Science. Proceedings*” (Romania, 2019).

Scientific Publications

A total of 11 scientific papers were published on the topic of the dissertation, including:

- 5 articles in journals recommended by the Committee for Quality Assurance in the Field of Education and Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan;

- 4 papers in proceedings of international scientific and practical conferences;

- 1 article in the journal *Remote Sensing*, indexed in the *Web of Science* database (Q1 quartile, 91st percentile);

- a textbook published in the state language for the discipline “*Geodesy.*”

Structure and Volume of the Dissertation

The dissertation consists of an introduction, four chapters, a conclusion, and a list of 103 references. The total volume of the work is 126 pages and includes 74 figures.

MAIN CONTENT OF THE DISSERTATION

The first chapter of this dissertation examines the structural characteristics of power network objects, safety requirements, and modern trends in monitoring technologies. In particular, it provides a detailed analysis of the geometric features of power line supports, their role in ensuring the stability of power transmission lines, and the main risks arising from their deformation or destruction. Special attention is given to regulatory requirements for the operation of supports and corresponding methods of technical supervision.

A classification and comparative analysis of methods used to monitor the condition of power line structures are presented. These include both traditional visual and instrumental techniques (ground inspections, theodolites, laser rangefinders) and modern digital technologies: aerial photography, laser scanning (LiDAR), photogrammetry, unmanned aerial vehicles (UAVs), as well as methods based on machine learning and automatic data analysis. Their efficiency, accuracy, time consumption, and applicability under various conditions are compared based on published studies and practical examples.

An important aspect of this topic is the assessment of the potential and advantages of each approach. For instance, LiDAR technologies enable high-precision remote monitoring without power line shutdowns, while computer vision techniques can be applied for automatic damage and defect detection. On the other hand, traditional methods remain in demand due to their simplicity and low cost.

Thus, the first chapter establishes the theoretical and analytical foundation for further study of support reconstruction methods and the restoration of power transmission structures. Considering the growing requirements for digitalization and automation in infrastructure control, a systematic review and evaluation of current solutions represent an essential step toward the development of more efficient and cost-effective technologies for power line maintenance and monitoring.

The second chapter analyzes both traditional and modern approaches to 3D modeling and reconstruction of power line supports based on spatial data.

Initially, attention is given to manual and semi-automatic methods for constructing 3D models. Although manual techniques provide relatively high accuracy, they require substantial time and human resources, limiting their applicability to large-scale projects. Semi-automatic methods, by contrast, accelerate the modeling process by employing algorithms for point cloud analysis and predefined structural templates. These approaches offer a balance between accuracy and performance, especially in cases involving standard or typical support designs.

Further, stochastic methods based on probabilistic geometry are considered. Such methods account for uncertainty and noise in the source data and variability in the shapes of supports. They are particularly effective when dealing with incomplete or noisy datasets, for example, those obtained through LiDAR scanning under challenging weather conditions. The application of stochastic models

enhances the robustness and accuracy of reconstruction by simulating multiple possible configurations based on statistical characteristics.

Additionally, a heuristic reconstruction methodology is presented, based on accumulated experience, logical rules, and empirical relationships. Heuristic algorithms are used for recognizing repetitive patterns, filtering false detections, and optimizing reconstruction parameters. They are especially useful when processing large datasets where rapid decision-making and automation of analytical processes are required.

Altogether, the approaches reviewed in this chapter demonstrate a wide spectrum of tools for power line support reconstruction in real-world conditions. Their integration allows for the development of flexible and scalable solutions applicable to both local surveys and national-scale projects. The chapter concludes with a comparative analysis of the effectiveness of the described methods, forming the basis for their application in comprehensive monitoring and modeling systems.

The third chapter addresses methods and criteria for evaluating the accuracy of linear matching and approaches for improving reconstruction quality through projection analysis and point cloud processing.

The main indicator of linear matching quality is the degree of conformity between reconstructed line segments and their actual geometric shapes, including both straight and curved wire sections. Quantitative evaluation of accuracy involves metrics such as the root mean square error (RMSE) of residuals, the ratio of internal to external points, and projection errors on 2D planes.

To enhance accuracy, preprocessing and filtering of raw data play a critical role in reducing noise and outliers. Effective clustering methods, including those based on grid structures, assist in isolating significant linear segments from large point datasets. Particular emphasis is placed on integrating various algorithms to improve stability and precision in the matching process.

One of the most effective tools is the **Hough Transform**, which reliably identifies linear structures in point cloud projections even under noisy or incomplete data conditions. Probabilistic modifications of the Hough Transform demonstrate improved results when working with broken or short lines, simplifying the subsequent merging of segments into a unified model.

Additionally, the **RANSAC (Random Sample Consensus)** algorithm is examined for its robustness to outliers and ability to extract reliable models based on random data subsets. RANSAC provides high accuracy in recognizing complex wire configurations, including discontinuities and weakly expressed segments.

Overall, the chapter emphasizes that a combination of classical and modern algorithms achieves a high level of accuracy and reliability in reconstructing power lines based on geospatial data obtained from LiDAR and aerial imagery. Such approaches form a solid foundation for automated monitoring and maintenance systems of power transmission networks.

The fourth chapter provides a comprehensive analysis of the method for reconstructing power line supports using abstract template structures derived from airborne LiDAR scanning (ALS). Based on high-density point cloud data collected

with a **RIEGL VUX-1** device, the study explores methods for accurately describing the geometric shapes of supports and automatically constructing their 3D models.

As a result of the conducted experiments:

- The key parameters used in the decomposition and reconstruction stages were precisely defined (thresholds for height and width, reliability coefficients, RANSAC thresholds, etc.);
- The performance of models and accuracy of alignment were evaluated depending on the type of support structure;
- It was demonstrated that sampling distance and point density directly influence model quality;
- The results of 3D reconstruction provide accurate spatial positioning of support elements, forming the basis for automatic safety assessment of power lines.

The proposed method enables semi-automatic modeling of complex support structures with high accuracy and significant time savings. The obtained results are suitable for further large-scale application — in automation of deformation control, identification of hazardous zones, and technical inspection of supports.

The use of LiDAR technologies in modeling and reconstructing power line supports:

- reduces time expenditures by several orders of magnitude;
- increases measurement accuracy;
- decreases the need for labor and logistical resources;
- enables automatic digital data processing.

Consequently, this approach offers high economic efficiency compared to traditional methods and represents an optimal solution for large-scale research.

According to the results of the economic analysis, the use of LiDAR technologies for 3D modeling and technical inspection of power transmission lines demonstrates a Return on Investment (ROI) of 200%. This figure confirms the high efficiency of the LiDAR approach compared to traditional geodetic methods. Moreover, the high ROI level allows for the effective application of this method across extensive territories.

CONCLUSION

The dissertation is devoted to the topic “Improving the methodology of 3D reconstruction of overhead power transmission pylons based on geospatial data” This research is particularly relevant in the context of digitalization of energy infrastructure, enhancing the efficiency of technical maintenance, and implementing remote monitoring systems.

The vast territory of Kazakhstan, its complex terrain and climatic conditions, as well as the limited human and material resources, reduce the efficiency of traditional methods used to assess the technical condition of overhead power line supports (OPLS). In this regard, the improvement of 3D modeling methods based on geospatial technologies — such as LiDAR, photogrammetry, aerial and satellite imagery — represents a modern and significant scientific task.

The **main objective** of this dissertation is to improve the methodology of 3D reconstruction of OPLS supports using geospatial data. To achieve this goal, several important scientific and practical tasks were addressed:

- A comprehensive review of modern methods for modeling OPLS structures was conducted, identifying their effectiveness and limitations;
- Algorithms were proposed to improve the accuracy of linear identification and automatic reorientation of supports;
- A component-based algorithm was developed, dividing support structures into three main parts (lower, middle, and upper) according to their geometric characteristics;
- Through a combined application of 2D Alpha-shape and RANSAC algorithms, both internal and external structures of supports were identified, along with their topological relationships, followed by precise calculation of their 3D coordinates.

The research results were tested on real point cloud data, demonstrating significant advantages of the proposed methods compared to traditional approaches — both in modeling accuracy and automation level. The developed algorithms effectively recognize complex support structures, restore their spatial configuration, reduce time costs, and minimize human-factor risks.

The **scientific novelty** of this research lies in the development of a component segmentation algorithm for OPLS supports based on their three-level structural division, as well as in the use of a combined (2D Alpha-shape + RANSAC) approach for precise 3D modeling with consideration of topological connections among structural elements.

The **validity and reliability** of the obtained scientific results are confirmed by the following:

- The methods and algorithms were selected considering the geometric and structural characteristics of supports, an extensive review of scientific literature, and international best practices;
- All proposed solutions were integrated into a single methodology and tested on real-world data;

- Algorithm efficiency was experimentally verified using LiDAR and photogrammetric data from actual OPLS sections;

- The results were compared with traditional and alternative approaches, revealing clear advantages in modeling accuracy, processing speed, and automation level.

The **practical significance** of this work is that the results can be directly implemented in digital management of energy infrastructure. 3D modeling of supports enables remote monitoring, prediction of technical failures, and optimization of preventive maintenance, thereby reducing operational costs and improving grid reliability.

The results of this dissertation were integrated into the educational process at **Satbayev University** and applied in several industrial projects, confirming their practical effectiveness. Furthermore, the scientific findings were presented at international and national conferences, where they received positive feedback from the professional community.

A total of 11 scientific papers have been published on the dissertation topic, including articles in reputable international journals and academic teaching materials.

Overall, this dissertation represents a significant **scientific and practical foundation** for further research and applied developments in the fields of energy, geoinformation systems, remote sensing, and digital modeling. The obtained results can serve as a basis for future studies and promote the integration of new technologies into industrial practice.

All the stated goals and tasks of the dissertation were fully achieved. The scientific and practical aspects of improving the 3D reconstruction methodology of OPLS supports based on geospatial data were comprehensively analyzed. Considering the complex geometric features of supports, a component-based segmentation model was proposed, integrating 2D Alpha-shape and RANSAC algorithms for topological analysis and 3D coordinate calculation. The results were validated experimentally and through comparative analysis with traditional methods, proving both the scientific and practical relevance of the proposed solutions.

The scientific results of the dissertation can be effectively applied in the following areas:

- **Energy infrastructure management systems** – automation of 3D model generation enables optimization of maintenance and failure prediction;

- **Geoinformation systems (GIS)** – accurate spatial data on supports can be integrated into digital maps for visual and analytical infrastructure control;

- **Remote sensing and monitoring** – regular observation of power line objects using satellites and UAVs (drones);

- **Education and research** – results were introduced into educational programs at Satbayev University in courses such as *Geodesy*, *Digital Engineering*, and *GIS Technologies*.

The input data included LiDAR scanning, photogrammetric imagery, point clouds, and vector and raster maps obtained for specific OPLS sections.

The technical and economic efficiency of the proposed 3D reconstruction methodology is confirmed by the following indicators:

- **Reduced maintenance time** – automated processing reduces labor costs by 30–40% compared to traditional methods;
- **Minimized human-factor influence** – eliminates the need for work in hard-to-reach or hazardous areas;
- **Improved accuracy and reduced errors** – modeling precision reaches up to 95% due to advanced segmentation and analytical algorithms;
- **Optimized maintenance costs** – enables more accurate planning of repairs based on digital models;
- **Long-term reliability** – regular updates of digital data ensure stable operation of OPLS systems.

Thus, implementation of this methodology contributes to reducing production costs and improving operational efficiency.

The scientific results obtained in this dissertation are comparable with leading international studies in geoinformatics and remote sensing:

- In works published in leading journals such as *Remote Sensing*, traditional RANSAC or machine learning approaches are often applied, but they have limited accuracy when dealing with complex geometrical structures of supports.
- This study proposes a **three-level component model** (lower, middle, and upper parts), enabling more precise segmentation and classification of structural elements.
- The **combination of 2D Alpha-shape and RANSAC algorithms** made it possible not only to segment objects but also to accurately determine topological relationships between angular points, providing precise spatial reconstruction.

Hence, the scientific level of the research fully meets modern international standards and enhances existing approaches with new efficient methods applicable both in research and in industrial practice.

The main content of the dissertation has been published in the following scientific works:

1. Shichao Chen, Cheng Wang, Huayang Dai, Hebing Zhang, Feifei Pan, Xiaohuan Xi, Yueguan Yan, Pu Wang, Xuebo Yang, Xiaoxiao Zhu, Ardana Aben. Power Pylon Reconstruction Based on Abstract Template Structures Using Airborne LiDAR Data // *Remote Sens.* 2019, 11, 1579 Процентиль 92,809 ISSN: 20724292.

2. Aben A.S., Zhakypbek Y. *Analysis of the Importance of Restoring the Geodetic Network of the City During the Construction of the Almaty Metro* // *Bulletin of KazNITU*, Almaty, 2019, No. 2, pp. 88–92. ISSN 1680-9211.

3. Aben A.S., Zhakypbek Y., Asetkyzy A. *Study of the Importance of Metro Construction in a Megapolis for Improving Passenger Flow and Creating Its Geodetic Reference Network* // *Mining Journal of Kazakhstan*, Almaty, 2019, No. 4, pp. 12–15. ISSN 2227-4766.

4. Zhakypbek Y., Kalybekov T., Tursbekov S.V., Aben A.S. *Efficiency of Using Laser Scanning on the Example of the Maleev Deposit* // *Mining Journal of Kazakhstan*, 2023, No. 4, pp. 48–52.

5. Kenzhekhan E.B., Zhakypbek Y., Kozhaev Zh.T., Aben A.S. *Creation of a Plan-Height Reference Map for the Zholbarysty, Shovan, and Kelinshektau Gold Deposits* // *Mining Journal of Kazakhstan*, 2023, No. 6, pp. 48–53.

6. Aben A.S., Dai H., Zhakypbek Y., Kumiskhanova B.B. *Geodetic Processing of LiDAR Data in the Reconstruction of Power Line Tracks* // *Mining Journal of Kazakhstan*, 2025, No. 3, pp. 18–24.

7. Aben A.S., Asetkyzy A., Zhakypbek Y. *Study of the Construction of Urban Geodetic Networks Using the Global Navigation Satellite System* // *Proceedings of the Satpayev Readings “Innovative Technologies – the Key to Solving Fundamental and Applied Problems in the Mining and Oil and Gas Sectors of the Economy of the Republic of Kazakhstan”*, 2019, Vol. 1, pp. 837–841. ISBN 978-601-323-145-7.

8. Aben A.S., Zhakypbek Y. *Analysis of the Application of Traditional Geodetic Methods in Metro Construction* // *Actual Questions and Innovations in Science. Proceedings – Craiova: Eurasian Center of Innovative Development “DARA”*, 2019, pp. 82–85. ISBN 978-601-341-174-3.

9. Toyshy A.B., Zhakypbek Y., Aben A.S. *Modeling of Mine Workings by Laser Scanning of the Drilling Trench* // *Development of the Mining and Metallurgical Complex of Kazakhstan in the Framework of the State Investment Project. Proceedings of the International Scientific and Technical Conference*, Almaty: Satbayev University, 2022, pp. 238–241.

10. Bektas A.D., Aben A.S. *Geodetic Support of Linear Objects* // *Proceedings of the International Scientific and Practical Conference Dedicated to the 115th Anniversary of Corresponding Member of the Academy of Sciences of the Kazakh SSR A.Zh. Mashanov and the 100th Anniversary of Academician Zh.S.*

Erzhanov “Innovative Technologies in Geospatial Digital Engineering”, Almaty, 2022, pp. 56–61.

11. Aukazhieva Zh.M., Kalybekov T., Aben A.S., Muratova A.M. *Geodesy (Textbook)*. Almaty: New Book, 2021.