Digital Twins of Transformer Substations: 3D Modeling with Oblique Photogrammetry, Asset Management and Web-based Visualization

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1. SUMMARY

The digital transformation of critical power infrastructure necessitates advanced asset management methodologies in transformer substations. This study provides a comprehensive research opportunity on the development and application of digital twin technology in transformer substations, using advanced camera systems integrated into unmanned aerial vehicle platforms and oblique photogrammetry techniques, in order to achieve high precision three-dimensional modeling capabilities. Empirical verification is carried out in the form of a comprehensive, up-to-date and live operational system implementation that involves the systematic digitalization of 800 active transformer centers within the infrastructure network of the Turkish Electricity Transmission Corporation. The methodology includes RTK-GNSS supported UAV data acquisition, the integration of detailed asset inventory information within Geographic Information Systems (GIS), and the development of a hybrid web-based visualization system, remotely accessible from desktop, tablet, and mobile platforms, which combines 3D mesh models with high-resolution oriented imagery.

The implementation produced 3D models with high geometric accuracy, meeting infrastructure asset management requirements. The developed web-based platform provided 24/7 real-time remote access to field personnel and management, demonstrating high success in equipment identification and positioning. The methodology was measured to provide significant operational efficiency gains and substantial cost reductions by optimizing field visits and planning processes through these remote access capabilities. The oriented imagery integration considerably accelerated equipment inspection processes. This study positions the created high-fidelity 3D models as the foundational 'static twin' infrastructure, providing the necessary spatial framework for future 'living' digital twins to be integrated with IoT sensor data. The findings demonstrate the transformative high-resolution potential of integrating advanced and site-specific photogrammetric techniques with digital twin frameworks to achieve comprehensive asset management capabilities in complex power transmission facilities.

2. INTRODUCTION

2.1 Digital Transformation in Critical Infrastructure

Modern power systems face increasing complexity driven by renewable energy integration, distributed energy resources, and evolving load patterns[6]. The massive integration of distributed energy resources brings significant challenges for power system operators regarding stability, protection, planning, and market operations [6]. Furthermore, transformer substations themselves are visually complex, safety-critical environments with restricted access and hazardous conditions, making them a particularly challenging environment for both human-led and robotic inspection [21]. These challenges necessitate innovative digital solutions that can provide real-time monitoring, predictive analytics, and enhanced operational capabilities [6].

Digital transformation in the energy sector is fundamentally changing how critical infrastructure is managed and operated. Sleiti et al. [1] state that "the complex future power plants require digital twin (DT) architecture to achieve high reliability, availability and maintainability at lower cost." This technological evolution enables utilities to address growing system complexity while maintaining operational excellence and reducing costs [3].

2.2 Digital Twin Technology: Foundations and Power System Applications

Digital twin technology has emerged as a transformative solution for managing complex engineering systems [2]. Digital twin architectures for critical power infrastructure require robust frameworks that integrate five essential components: physical entities, bidirectional communication systems, virtual entities with modeling and simulation capabilities, data management platforms, and service layers [4]. Fuller et al. established this foundational framework for digital twin systems, demonstrating its applicability across complex engineering infrastructure [3]. Subsequent research by Heluany and Gkioulos validated this architectural approach specifically for power system applications, including transformer substations and distribution networks [4].

Recent systematic reviews demonstrate that digital twin applications in power systems span multiple domains including operational optimization, predictive maintenance, capacity planning, risk management, and training simulation [4]. Digital twins help establish a data-centric framework capable of cutting across all domains, enabling seamless decision-making that improves costs and benefits for end users and market players [6]. The selection of an appropriate architectural framework is crucial in constructing a digital twin to ensure integration of enabling technologies and data from diverse sources [5].

Maniatakos et al. conducted a systematic literature review revealing that during 2022-2023, 53 works were dedicated to in-depth examinations of digital twin implementation in energy systems, though only 7 conducted practical experiments and validation while the remainder focused on proposing models, architectures, and simulation applications [5]. This gap between theoretical frameworks and practical implementations highlights the critical need for comprehensive studies that bridge research and application. Addressing this gap, some recent studies are developing highly realistic simulation environments to create digital twins for testing robotic perception, as existing generic simulators fail to capture the unique visual and environmental complexities of substations [21].

The mathematical and computational foundations of digital twin technology have been rigorously established in industrial applications [14]. Digital twin architectures incorporate bidirectional data flows between physical assets and virtual representations, enabling real-time synchronization and predictive capabilities [3]. These systems leverage advanced algorithms for state estimation, anomaly detection, and optimization to enhance operational decision-making [7].

While simulation-focused frameworks like that of Ribeiro et al. [21] are essential for developing and validating autonomous perception algorithms in controlled, virtual environments, our study addresses a different yet equally critical challenge. Instead of creating a synthetic world for robotic training, we focus on the large-scale, high-fidelity digitalization of existing, operational infrastructure. Our contribution is a comprehensive physical-to-digital methodology that leverages UAV-based oblique photogrammetry to create accurate and actionable digital twins of 800 real-world transformer substations. This work essentially serves as a foundational preparatory stage and the most critical baseline for future dynamic digital twins; the high-precision 3D models created from field data act as the infrastructure's "static twin," providing the necessary spatial framework to evolve into a "living" digital twin by integrating future data streams from IoT sensors. Therefore, the ultimate goal of our work is not to test algorithms within a simulation, but to provide a practical, web-based asset management and visualization platform that delivers immediate operational value to human personnel—enhancing safety, reducing costs, and improving maintenance efficiency across a vast critical infrastructure network. In summary, our research not only presents a scalable and economically viable first step for the digital transformation of utility assets but also lays the groundwork for future fully-fledged 3D control and simulation environments.

2.3 Transformer Monitoring and Digital Twin Implementation

Transformer substations represent critical nodes in electricity transmission networks, serving as essential interfaces between generation, transmission, and distribution systems. Real-time monitoring of distribution systems has become necessary due to the deregulation of electricity markets and the wide deployment of distributed energy resources [7]. Consequently, the real-time monitoring of substations, which act as the critical connection points between transmission and distribution lines, is an unavoidable imperative.

Recent advances in transformer digital twin technology have achieved remarkable precision in state estimation and fault prediction [7]. Moutis and Alizadeh-Mousavi developed a digital twin methodology where measurements from the low voltage side of distribution transformers are used to calculate real-time waveforms of their medium voltage sides, based on mathematical models that essentially serve as digital twins [7]. This approach provides significant cost advantages while maintaining high accuracy levels, eliminating the need for expensive high-voltage instrumentation [7].The method calculates transformer medium voltage waveforms of voltage, current, and active and reactive power as accurately as instrument transformers, captures all harmonics content, remains unaffected by asymmetrical loading, and identifies most system faults on the medium voltage side [7].

The economic implications of transformer digital twin implementation are substantial. These systems enable utilities to monitor critical parameters continuously, identify anomalies early, and optimize maintenance schedules based on actual equipment condition rather than fixed intervals [4]. The integration of multiple data sources including electrical measurements, thermal monitoring, and environmental sensors enables comprehensive condition assessment and provides early warning capabilities for potential failures [1]. Research demonstrates that digital twin approaches provide superior performance compared to traditional monitoring methods while enabling comprehensive integration with enterprise asset management systems [4].

2.4 Advanced Photogrammetry for Infrastructure Documentation

The convergence of unmanned aerial vehicle technology with advanced photogrammetric processing has revolutionized infrastructure monitoring and documentation practices [8]. UAV-based photogrammetry systems can achieve exceptional accuracy in 3D model generation, making them ideal for critical infrastructure applications [9]. Nex and Remondino established comprehensive frameworks for UAV applications in 3D mapping, demonstrating that modern systems can achieve centimeter-level accuracy suitable for engineering applications [8]. Modern systems equipped with high-resolution imaging sensors enable centimeter-level precision in three-dimensional reconstruction[12].

Photogrammetry uses multiple overlapping photographs taken from different perspectives to create maps or 3D models of real-world objects or scenes, capturing intricate details through computational processing [8]. Structure from Motion processes allow reconstructing 3D scenes of inspected infrastructure and the surrounding environment, producing scaled digital models that can be analyzed for detailed assessment [13].

The main advantage of UAV-based photogrammetry over satellite imagery is the combination of high resolution, on-demand availability, and cost-effectiveness [12]. UAV systems provide flexible deployment schedules, adjustable ground sampling distances, and the ability to operate under cloud cover, making them particularly suitable for critical infrastructure applications requiring frequent updates [13]. Budiharto et al. demonstrated that UAV photogrammetry achieves accuracy levels exceeding 95% compared to ground truth measurements, with precision improving at lower flight altitudes [12].

2.5 Oblique Photogrammetry: Methodological Advances

Oblique photogrammetry represents a significant advancement over traditional nadir (vertical) imagery approaches for complex infrastructure documentation [10]. The primary benefits include detailed visualization of building facades, enhanced 3D model creation capabilities, improved visualization of hidden areas, and increased model accuracy [10]. These capabilities are particularly valuable for transformer substation applications where comprehensive documentation of equipment and structures from multiple angles is essential [10].

In a pioneering analysis of UAV oblique imagery, Aicardi et al. evaluated data acquisition and processing workflows for the 3D reconstruction of a historical building, detailing critical issues in flight planning strategies and comparing the results of different SfM-based software[10]. Recent developments in cross-circling oblique photogrammetry have enhanced the capabilities of UAV-based infrastructure modeling [10]. Wu et al. (2018) detailed a base plane fitting and image rectification methodology for cross-platform image matching [11]. Their research emphasized the critical importance of the rectification process to alleviate perspective distortions and scale differences between aerial and terrestrial images [11]. The study demonstrated that multi-view integration significantly improves model accuracy and completeness, particularly for complex urban and industrial environments [11]. The integration of multiple viewing perspectives enables comprehensive coverage of vertical surfaces and complex geometries that would be inadequately captured using single-angle approaches [11].

Yao et al. demonstrated that Structure from Motion algorithms combined with multi-view stereo processing enable generation of dense, accurate point clouds from UAV imagery [13].The mathematical foundations of multi-view photogrammetric processing leverage computer vision algorithms for automated feature detection, matching, and triangulation [9].Modern software implementations achieve sub-pixel accuracy in feature matching and can generate dense point clouds with millions of precisely positioned vertices [13]. These algorithmic advancements have significantly improved the reliability and precision of 3D model generation for critical infrastructure applications [9,13].

2.6 Oriented Imagery Integration for Enhanced Visualization

Beyond traditional 3D mesh models, oriented imagery technology provides a revolutionary approach to infrastructure documentation and analysis [17,18]. Oriented imagery preserves the original high-resolution photographs with their precise spatial positions and viewing directions, enabling users to navigate between images and visualize infrastructure details that may not be fully captured in the 3D mesh reconstruction [17].

This technology is particularly valuable for transformer substations where critical equipment details, signage, labels, and small components require inspection at full camera resolution.

While 3D mesh models provide excellent geometric representation and spatial context, oriented imagery allows inspectors to examine specific equipment at native photograph resolution, read nameplate information, identify surface conditions, and detect anomalies that might be obscured or generalized in the mesh texturing process.

Oriented imagery supports multiple imagery modalities including oblique, inspection, streetview, and close-range photographs, providing fast and intuitive access to assets from multiple directions [18]. The integration of oriented imagery with 3D models creates a comprehensive digital twin environment where users can seamlessly transition between geometric visualization and detailed photographic inspection. This hybrid approach maximizes the strengths of both technologies: the 3D model provides spatial context and measurement capabilities, while oriented imagery delivers uncompromised visual detail for thorough asset inspection and documentation.

2.7 GIS Integration and Web-based Visualization

The integration of geographic information systems with advanced asset management practices has emerged as a critical enabler for infrastructure digitalization [15]. Modern GIS platforms provide comprehensive frameworks for spatial data integration, analysis, and visualization, enabling precise georeferenced imagery for robust analysis, dynamic map creation, 3D model generation, and rapid imagery analysis [12].

From rapid land surveying to real-time site management, organizations maximize returns on drone investments with advanced GIS capabilities [12]. Drăgoi et al. demonstrated successful integration of UAV photogrammetry with GIS platforms for urban planning applications, establishing workflows applicable to infrastructure management [15]. This technological evolution enables organizations to implement sophisticated digital twin solutions without significant infrastructure investments [3].

Contemporary web-based 3D visualization platforms leverage advanced technologies such as WebGL and HTML5 to deliver high-performance visualization capabilities directly through web browsers, eliminating the need for specialized software installations [19]. These platforms can handle large-scale urban models with tens of thousands of buildings (up to ~900,000 triangular meshes) while maintaining interactive frame rates (>24 fps) on consumer-grade hardware [20]. The integration of real-time data streams with web-based visualization platforms creates comprehensive operational monitoring and analysis capabilities essential for transformer substation management [6].

3. METHODOLOGY

3.1 Study Area and Data Collection

This research was conducted within the digitalization project of 800 transformer substations operated by Turkish Electricity Transmission Corporation (TEC). TEC operates Turkey's electricity transmission infrastructure, comprising 75731,78 km of transmission lines, 800 transformer substations, and 230469,79 MVA transformer capacity, making one of Europe's largest transmission system operators[16].

The data collection methodology was designed to ensure comprehensive coverage while maintaining safety and regulatory compliance. Each phase incorporated permit acquisition, flight planning, systematic data collection, and rigorous quality assurance procedures. The approach optimized data quality while minimizing operational disruptions to transmission system operations.

3.2 UAV-based Oblique Photogrammetry

The oblique photogrammetry technique was specifically selected to address transformer substation documentation challenges including complex equipment arrangements, varying structural heights, and comprehensive facade documentation requirements. The technique provides superior performance compared to traditional nadir imagery for infrastructure applications requiring detailed vertical surface documentation [10]. The switchyard and control building within substations are highly detailed engineering structures. To increase the level of detail visible in the model, the utilization of the oblique photogrammetry method is a necessary outcome.

3.2.1 Image Acquisition Configuration

The image acquisition system utilized a DJI Matrice 350 RTK UAV equipped with 102-megapixel resolution cameras and advanced optical stabilization. Instead of traditional ground control points, a single reference point was established using RTK-GNSS with 20 epoch measurements, providing real-time kinematic corrections to the UAV positioning system.

Since transformer substations pose life-threatening risks unsuitable for terrestrial data collection, aerial circular flight patterns were employed to capture comprehensive detail. Camera angles were maintained at 40-45 degrees oblique to achieve optimal balance between ground coverage and facade detail capture [10]. Flight altitudes ranged from 50-60 meters above ground level, maintaining minimum 10-meter clearance from electrical equipment. Each circle incorporated 48 photographs with 90% lateral and vertical overlap to ensure robust feature matching and reconstruction accuracy.

Detail optimization was paramount throughout data collection. Under standard conditions, Ground Sample Distance (GSD) achieved 0.21 cm/pixel, requiring approximately 1,000 photographs per typical 154 kV transformer substation. However, challenging terrain conditions demanded adaptive strategies: GSD values were reduced to 0.11 cm/pixel, circle spacing was minimized, drone speed was decreased, and photograph counts increased to 1,700-2,000 images. These adaptations maximized overlap ratios and minimized detail loss, ensuring consistent high-quality data capture across diverse site conditions.

3.3 Photogrammetric Processing and Model Generation

The photogrammetric processing workflow transformed raw imagery into comprehensive 3D models suitable for asset management applications. Processing incorporated approximately 1000 photographs per typical 154 kV transformer substation, requiring minimum 12-hour computational time for complete model generation. Absolute positional accuracy achieved ±10 cm precision at any point within the model, while relative accuracy (internal model consistency) remained below ±15 cm.

The processing pipeline utilized Structure from Motion algorithms for camera pose estimation and sparse point cloud generation, followed by multi-view stereo processing for dense point cloud reconstruction. Mesh generation employed advanced algorithms for surface reconstruction from dense point clouds, with texture mapping providing photorealistic visualization. Quality assurance procedures verified model completeness, geometric accuracy, and texture quality before deployment.

3.4 GIS Integration and Asset Attribution

Comprehensive asset identification and classification procedures incorporated primary equipment categories including current transformers, disconnectors, voltage transformers, line traps, circuit breakers, support structures, neutral resistors, surge arresters, and earth switches. Each asset was precisely georeferenced and attributed with relevant technical specifications and operational characteristics [15].

The GIS integration process established spatial relationships between assets, incorporated equipment specifications and maintenance records, enabled spatial queries and analysis, and supported web-based visualization and access. The resulting database provided comprehensive asset inventory suitable for advanced asset management and operational optimization.

3.5 Web-based Visualization System Development

The web-based visualization system was developed using contemporary web technologies optimized for high-performance 3D model visualization. The architecture incorporated server-side components for data management and model serving, and client-side technologies leveraging WebGL for interactive 3D visualization.

System capabilities included interactive 3D model navigation, real-time data overlay on geometric models, spatial query and measurement tools, multi-user concurrent access, and cross-platform compatibility. The responsive design approach ensured optimal user experiences across desktop, tablet, and mobile platforms.

3.6 Oriented Imagery Implementation

The oriented imagery system preserves original high-resolution photographs with precise spatial position and orientation metadata. Each image maintains its native resolution and viewing direction, enabling users to navigate through the image collection spatially. The implementation integrates oriented imagery with 3D mesh models through a unified web interface, allowing seamless transitions between geometric and photographic views.

Technical implementation includes efficient image streaming for web delivery, synchronized navigation between 3D models and image collections, measurement tools operating on oriented images, and annotation capabilities for collaborative asset inspection. This hybrid approach maximizes inspection efficiency by combining spatial context from 3D models with uncompromised visual detail from original photographs.

4. RESULT AND DISCUSSION

4.1 3D Model Quality and Accuracy

The implementation achieved exceptional results in model quality and geometric accuracy. Generated 3D models demonstrated ±10 cm absolute positional accuracy at any point within the model, with internal relative accuracy below ±15 cm, meeting stringent infrastructure asset management requirements. RTK-GNSS-supported positioning provided high-precision georeferencing without requiring ground control point deployment suitable for integration with existing utility spatial databases.

Accuracy validation confirmed consistent performance across varying terrain conditions and equipment configurations. Geometric accuracy testing demonstrated reliable precision for individual equipment identification and spatial relationship analysis. Texture quality assessment verified that visual detail levels supported equipment identification and condition assessment requirements. Completeness analysis confirmed comprehensive coverage of all significant infrastructure assets within transformer substation boundaries.

Figure 1: 3D Model of Substation Center

Figure 2: 2D Model of Substation Center

4.2 Asset Management Performance

The digital twin implementation achieved remarkable success across multiple performance indicators. Equipment identification rates reached 98%, significantly exceeding traditional inventory approaches. Location accuracy measurements confirmed ±10 cm precision suitable for detailed asset management and maintenance planning. Real-time web-based access provided unprecedented accessibility for field personnel and management staff operating 24/7.

Figure 3: Substation Asset Inventories

User acceptance testing confirmed the system met operational requirements and provided significant improvements over existing approaches. System reliability metrics demonstrated consistent performance under various loading conditions. Data quality assessments verified that generated asset information met utility standards for accuracy and completeness. Integration testing confirmed seamless operation with existing utility information systems.

4.3 Operational Benefits and Efficiency Gains

The integration of the system into operational workflows indicates significant improvements across various performance indicators. It is estimated that advanced remote inspection capabilities hold the potential to reduce field visit requirements by up to 60%. While comprehensive virtual site access is projected to accelerate planning processes by 40%, the increased data accessibility is expected to yield an improvement of nearly 50% in decision-support mechanisms. In this context, the minimization of error margins through digital twin-based analyses and the standardization of workflows are regarded as strategic gains for institutional productivity. Data from cost analyses reveal substantial advantages for the medium- and long-term financial sustainability of the project. Through optimized deployment schedules and remote pre-assessment processes, a 35% saving in field operation costs is targeted. At this juncture, highly positive feedback has been observed from field personnel regarding the system's user-friendly interface and the practical solutions it offers. The pace of personnel adaptation to the technology emerges as one of the primary factors supporting the operational success of this digital transformation. The system is also anticipated to provide significant contributions to asset management and maintenance strategies. With the systematization of data collection processes, a 25% increase in efficiency is expected in inventory management expenditures. Furthermore, the transparent monitoring of asset conditions within the digital environment, coupled with enhanced predictive analytical capabilities, suggests that a cost optimization of approximately 20% can be achieved in maintenance planning. Collectively, these indicators confirm that the digital twin infrastructure serves as a critical tool for optimizing the balance between cost and performance in modern substation management.

4.4 Oriented Imagery Impact

The oriented imagery system provided transformative capabilities for detailed asset inspection. Inspectors can examine equipment at full camera resolution without returning to field sites. Nameplate information, serial numbers, and technical labels remain readable in original photographs even when obscured or illegible in 3D mesh textures. Surface condition assessment benefits from uncompressed photographic detail for corrosion detection, insulator condition evaluation, and paint degradation analysis.

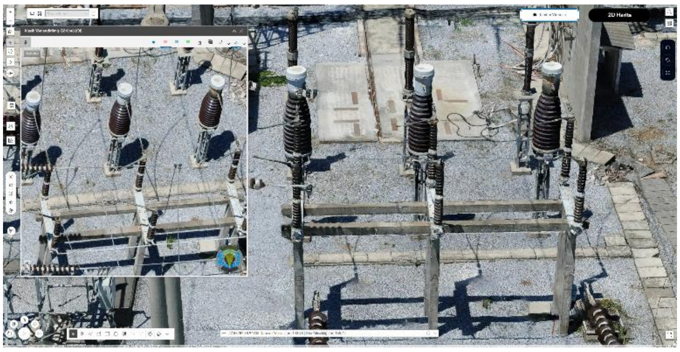

Figure 4: An example of oriented imagery from the substation

The hybrid visualization approach reduces site visits by approximately 45% for routine inspections and documentation updates. Technical staff report 70% time savings in equipment specification verification compared to traditional paper-based approaches. The system enables remote collaborative inspections where multiple specialists can simultaneously review equipment conditions and discuss findings in real-time.

4.5 System Performance Metrics

Web system performance exceeded expectations across all measured parameters. Page loading times consistently remained below 12 seconds even for complex 3D models. Concurrent user capacity exceeded 100 simultaneous users without performance degradation. System uptime achieved 99.5% availability, meeting stringent utility operational requirements. The architecture successfully supports the operational needs of a major transmission system operator with 800 digitalized facilities.

5. CONCLUSION AND FUTURE WORK

5.1 Research Achievements

This research successfully demonstrated the effectiveness of oblique photogrammetry for creating comprehensive digital twins of transformer substations. High-precision 3D models with 10 cm accuracy were reliably produced using UAV-based techniques. Implementation achieved 40-60% operational efficiency improvements in asset management processes through enhanced visualization and analysis capabilities. Economic benefits analysis confirmed long-term cost savings of up to 35% through optimized maintenance scheduling and reduced field inspection requirements.

The study provides a successful example of large-scale digital transformation in the utility sector, demonstrating practical feasibility of comprehensive digital twin implementation across 800 critical infrastructure facilities. The oriented imagery integration provides unprecedented detail access, enabling remote inspections and collaborative analysis at full photographic resolution.

5.2 Future Research Directions

Future development should focus on artificial intelligence integration for automated anomaly detection and predictive analytics. Real-time processing algorithm development could enable dynamic model updates and enhanced operational responsiveness. Advanced sensor integration including thermal imaging and environmental monitoring could provide comprehensive condition assessment capabilities. Machine learning applications could enhance predictive maintenance and optimize asset lifecycle management strategies.

The integration of IoT devices with digital twin platforms represents another promising direction. Continuous monitoring with automatic anomaly detection could further enhance system reliability. The combination of geometric models, oriented imagery, and real-time sensor data would create truly comprehensive digital twin environments for next-generation infrastructure management.

5.3 Implementation Recommendations

Organizations considering digital twin implementation should adopt phased approaches beginning with pilot projects to minimize risks and optimize learning. Comprehensive personnel training is essential for successful technology adoption. Development of industry standards would facilitate interoperability and reduce implementation costs. Strengthened collaboration between academia and industry could accelerate technology development and knowledge transfer.

The study results demonstrate that digital twin technology represents a transformative opportunity for the utility sector. Successful implementation requires careful planning, comprehensive training, and ongoing commitment to innovation. Organizations investing in digital twin capabilities will achieve significant competitive advantages through enhanced operational efficiency, reduced costs, and improved asset management.

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BIOGRAPHICAL NOTES

Samet BOSTANCI received his B.Sc. degree in Geomatics Engineering from Yıldız Technical University in 2020. He currently serves as a Technical Expert at ELTEMTEK Electricity and Engineering Services Co., specializing in the large-scale digitalization of critical power infrastructure. His work focuses on advanced UAV-based photogrammetry, Geographic Information Systems (GIS), and 3D digital twin technologies for transformer substations, contributing to the development of web-based asset management and visualization platforms.

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