Enhancing Reality Capture for Electrical Substations with Integrated Spherical Images and GeoBase Data in a GIS Platform

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ABSTRACT

The complex task of three-dimensional (3D) modeling for high-voltage electrical substations presents a multifaceted challenge, integrating numerous technical and practical factors. Recent advancements in geospatial technology have led to a revolutionary change in the digitization and management of critical infrastructure, particularly within high-voltage electrical substations. This study introduces a methodology centered around reality capture utilizing georeferenced 360-degree (spherical) images. This approach allows for a full capture of the environment that is linked to geographical coordinates. The result is a hybrid virtual environment where real-world elements can seamlessly blend or overlay onto virtually modeled objects. The developed system offers an intuitive navigation interface intricately linked with the georeferencing of spherical images. This interface enhances the precision of visualizing equipment within the substation yard, aiming to streamline equipment interaction, mitigate risks in hazardous and confined areas, simplify equipment identification and location through computer vision-assisted recognition, and furnish more detailed and specific information for geopositioned 3D reality capture in CAD or GIS layouts. Initial testing has showcased promising outcomes in terms of accuracy, user engagement, and a notable enhancement in operational efficiency. This work contributes to the growing field of study in virtual environments dedicated to infrastructure management, providing the groundwork for enhanced remote automated inspection operations filled with information.

Keywords: 360-Degree Images, Geospatial Technologies, CAD Layout, HVDC, Electricity Substations, Virtual navigation in Restricted Area, Maintenance and interaction with HVDC Equipment.

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1. INTRODUCTION

In a rapidly evolving energy landscape, electric utility companies are compelled to embrace digital transformation for greater efficiency and sustainability. A key element of this transformation involves effective asset management to ensure that investments align with strategic goals and deliver maximum value, as emphasized by Mondragón Bernal et al (2022). Optimizing asset management practices offers numerous benefits, including increased equipment lifespan, enhanced productivity, optimized maintenance costs, improved employee safety, greater energy efficiency, and higher profitability.

In the specific realm of managing, maintaining, and securing critical infrastructures, particularly equipment in high-voltage electrical substations, adopting efficient and reliable approaches is imperative. In this context, the integration of geospatial technology, 3D modeling, and reality capture techniques plays a crucial role, as highlighted by Li, Ruiheng, et al (2023). Furthermore, the incorporation of Virtual Reality (VR) systems brings about a transformative leap in user interfaces, providing an immersive three-dimensional experience that transcends traditional limitations, as mentioned by Radianti (2020). VR fosters a heightened sense of immersion, aligning mental models with real-world field operations, as discussed by Sebok et al (2002), making it a fundamental tool for overcoming the limitations of 2D interaction spaces in the power generation industry, as noted by Azuma and L (1997).

In the power generation sector, where safety is paramount and process optimization is crucial for cost reduction, Virtual Reality emerges as a promising solution. However, the swift resolution of issues in power stations or transmission networks requires qualified personnel, posing challenges in terms of availability and cost-effectiveness, as outlined by Wei et al. 2020. In this context, the efficient management and maintenance of critical infrastructures, such as electrical substations, demand innovative approaches. Georeferenced spherical photos emerge as a valuable resource for navigation and interaction in virtual electrical substations, as evidenced by Yu et al (2023).

Integrating these images into a 3D virtual environment allows users to explore and interact with equipment, closely mirroring real-world conditions. The rapid evolution of geospatial technologies introduces innovative solutions for managing and interacting with such infrastructures. The proposed methodology harnesses the power of geospatial technologies for virtual navigation and equipment interaction in substations, as emphasized by Zhu (2023). By incorporating georeferenced spherical photos into the virtual environment of a substation in VR, this approach ensures a secure and controlled environment for training and testing, simultaneously enhancing the efficiency and reliability of step-by-step activities, reducing time and costs associated with system maintenance. This comprehensive strategy aims to address the multifaceted challenges of the power generation industry, offering a promising path forward in safety, efficiency, and operational excellence in high-voltage electrical substations.

2. OBJECTIVES

The main objectives of the developed system, which utilizes georeferenced 360-degree images for high-voltage electrical substations, are as follows:

- **Facilitate Equipment Interaction:** The system aims to expedite the interaction between equipment within substations, allowing users to explore and interact with equipment in a way that accurately reproduces real-world conditions.
- **Mitigate Risks in Hazardous and Confined Areas:** The system's intuitive navigation interface is closely tied to the georeferencing of spherical images. This increases accuracy in visualizing equipment and substation yards, helping to mitigate risks in hazardous and confined areas.
- **Produce Detailed and Specific Information for Georeferenced 3D Reality Capture:** The system is designed to integrate with CAD, layouts, and GIS platforms, contributing to a precise and detailed representation of the substation environment.

Thus, the system not only aims to enhance equipment interaction and visualization but also seeks to increase safety, reduce risks, and provide detailed information for georeferenced 3D reality capture in CAD or GIS layouts. This contributes to a more efficient and secure management of high-voltage electrical substations. This system underscores the importance of integrating geospatial technologies, such as 360-degree images and drones, in the management and maintenance of high-voltage electrical substations. The convergence of these technologies with GIS and CAD systems brings significant benefits, optimizing inspection processes, aligning infrastructure projects with the terrain, and reducing operational costs.

3. METHODS

The proposed methodology involves a comprehensive approach, from capturing field images to utilizing the virtual environment, as illustrated in Figure 1. Initially, field operators use a 360-degree camera to capture detailed images of the substation, also recording information about each piece of equipment during the process.

Captured images undergo an information extraction process in Exchangeable Image File Format (EXIF), including crucial data such as date, time, GPS location, and camera orientation. These details serve as the basis for georeferencing the images, ensuring the precise location of equipment within the substation. Image processing and pattern recognition techniques are applied to identify specific objects in the images, such as equipment tags.

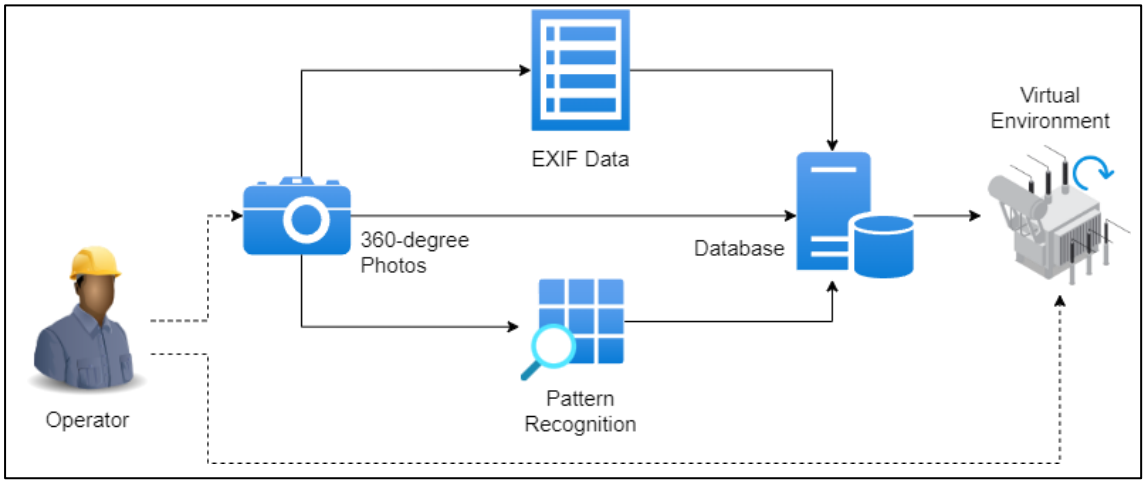

Figure 1- Diagram of proposed methodology.

The extracted data and operator records are stored in a centralized database, allowing easy updating and insertion of new information as new images are captured. These data support the 3D modeling of substation components. Additionally, based on this data, models are integrated into the virtual environment and positioned according to geospatial coordinates within the substation.

The insertion of captured photos into the virtual environment occurs in an overlaid manner, corresponding to the positions of the 3D models of the equipment, providing an accurate and contextualized visualization. This virtual environment is continuously updated whenever new images are captured, ensuring it accurately reflects changes in the substation over time.

The resulting system is accessed by operators, engineers, and maintenance teams for asset management, safety training, and operational planning. Interactive features are provided to facilitate analysis and decision-making, promoting an effective approach that prioritizes safety, efficiency, and innovation in the electric power sector.

A methodology using georeferenced 360-degree photos has been presented to enhance navigation and interaction in virtual electrical substations, highlighting results obtained in initial tests. The continuous integration of geospatial technologies offers a more detailed and comprehensive understanding of the environment, resulting in more efficient and secure management of high-voltage electrical substations.

Furthermore, it is imperative to examine the potential of seamlessly integrating GIS, CAD, 360-degree images, and drone images to drive innovation across various industries. This entails acknowledging the challenges and opportunities inherent in such integration.

- **Survey and Analysis of Geospatial Technologies:** A comprehensive survey is conducted on geospatial technologies, with a particular focus on GIS systems, CAD, 360-degree images, and drone images. This survey aims to identify their capabilities and applications in managing electrical infrastructures.
- **Integration of Geospatial Data:** A methodology is developed to integrate geospatial data from diverse sources. The objective is to create a holistic representation of the electrical substation environment.

- **Development of Methodology for Navigation and Interaction:** A methodology utilizing georeferenced 360-degree photos is proposed and developed to enhance navigation and interaction within virtual electrical substations.
- **Testing and Evaluation:** Initial tests of the proposed methodology are performed to assess accuracy, operational efficiency, and user engagement. These tests validate its applicability in managing high-voltage electrical substations.
- **Results Analysis and Discussion:** The results from the initial tests are analyzed, and the benefits and challenges of integrating geospatial technologies are discussed. Additionally, opportunities for improvement are identified.
- **Final Considerations and Recommendations:** Based on the results obtained, final considerations are presented along with recommendations to enhance the methodology. These recommendations aim to improve its application in real high-voltage electrical substation management environments.

4. PRELIMINARY RESULTS

The methodology proposed in this work was applied in *Araraquara* substation located in state of São Paulo – Brazil, operated by *Eletronorte/Eletrobras Group*. The substation was modeled using Autodesk Inventor, while the corresponding virtual environment was built using *Unity3D* to incorporate interactive features and navigation capabilities.

A total of 1274 high-resolution spherical photos were meticulously captured from various viewpoints within the substation. These images were accompanied by detailed EXIF information, including date, time, GPS location, and camera orientation, ensuring a robust foundation for subsequent geotagging processes and database integration.

Figure 2 presents a satellite image overlaid with CAD general arrangement of electrical assets, geolocated and matched with the image via an interface enabling zoom, pan, and layer control. A set of pins is superimposed on the map image, each accessible with a simple click, allowing the user to operate the spherical image. The yellow circle denotes the user's location, with the corresponding image presented in real time.

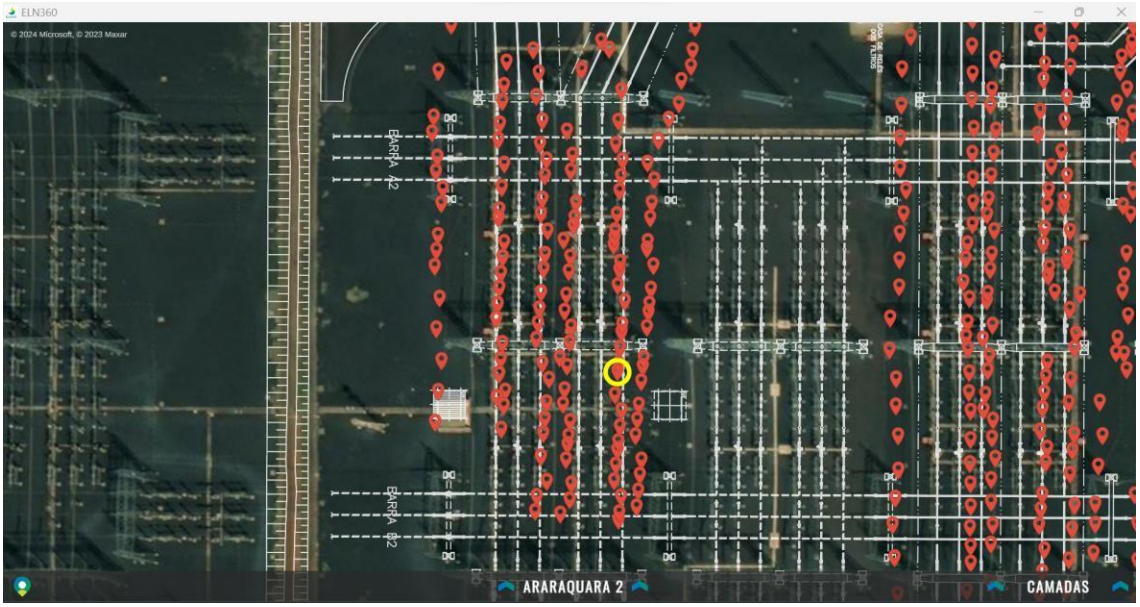

Figure 2-Set of Spherical Images location presented over satellite image geolocated.

Figure 3 shows the actual equipment in the field, providing visualization and interaction. These interactive features allow users to engage with the imagery in various ways. Photos can come from the server or stored locally, ensuring flexibility in accessing and managing the visual data. In preview mode, users have the freedom to freely rotate the photos, gaining different perspectives and insights into the equipment and its surroundings.

During interaction, users can seamlessly browse the available photos, enabling them to navigate through the visual data and gather detailed information as needed. This immersive experience enhances the user's understanding of the field equipment, facilitating informed decision-making and effective management of the electrical substation environment.

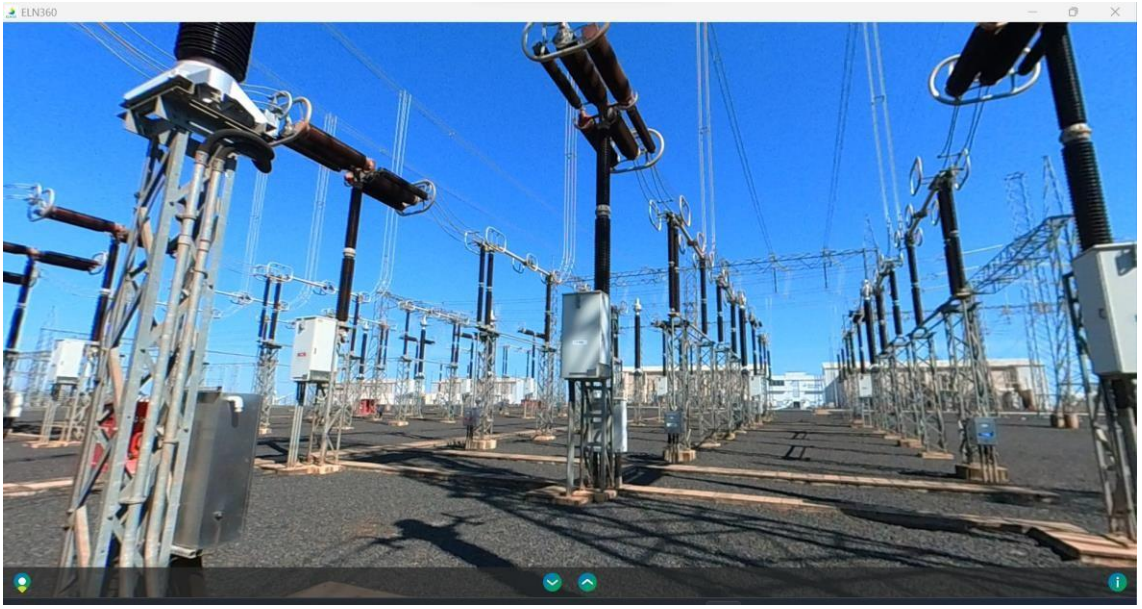

Figure 3- Spherical View of CA area set of images.

Figure 4 illustrates the substation map with the CAD overlaid, providing users with comprehensive insights into the layout and infrastructure of the facility. This integrated visualization allows users to analyze the substation in detail, facilitating effective planning and decision-making processes. When selecting layers, users can choose the type of CAD to be displayed, tailoring the visualization to their specific needs and preferences. Additionally, users have the option to overlay images captured by drones, further enriching the visual representation with real-world data.

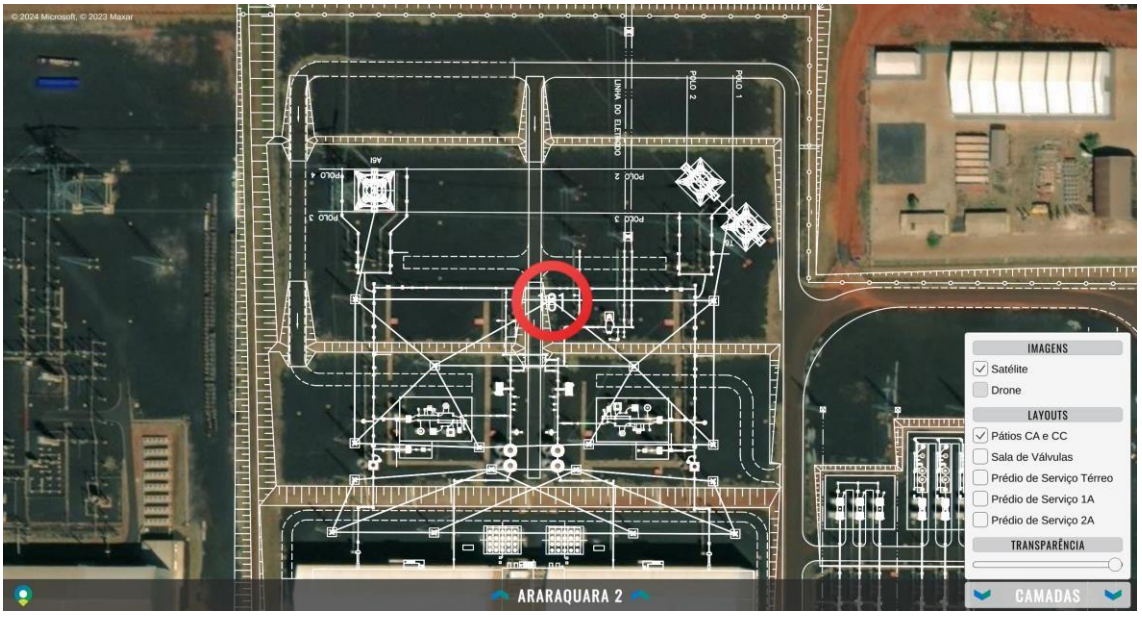

Figure 4- Map layers interactions.

Furthermore, users can adjust the opacity of CAD layouts, fine-tuning the visual balance between different layers for better clarity and understanding. Moreover, users have the flexibility to change the map server used, enabling them to seamlessly switch between different geographical contexts or sources of map data. This comprehensive set of features empowers users to explore and analyze the substation environment with precision and versatility, enhancing their ability to manage and maintain critical infrastructure effectively.

The proposed methodology facilitated the seamless insertion of georeferenced photos into the virtual environment. Each photo was represented by a virtual sphere positioned near the respective equipment within the virtual substation. This dynamic integration allowed for contextualized visualization within the virtual space, enhancing the understanding of the environment.

During preliminary user testing, participants navigated through the virtual environment effortlessly. By approaching a virtual sphere and executing a click, the corresponding 360-degree photo opened in the same spatial location within the virtual environment. This functionality enabled users to seamlessly transition between the virtual and real environments, offering an immersive and location-specific view of the substation, as demonstrated in Figure 5.

Figure 5- Virtual substation with inserted spheres (left) and a 360-degree photo opened in a specific position (right).

A crucial aspect under examination was the continuous updating of the virtual environment, achieved through the incorporation of new photos into the database while harnessing EXIF date and time information. The successful execution of these updates underscored the system's remarkable integration velocity, furnishing engineers with fresh insights promptly upon photo addition or modification. This capability played a pivotal role in bolstering operational efficiency and streamlining decision-making processes within the substation environment.

Moreover, the pattern recognition algorithm exhibited proficiency in identifying equipment tags and accurately placing corresponding photos in designated locations. However, ongoing refinement efforts are imperative to address identified challenges and optimize the overall efficacy of the methodology.

In summary, the initial findings stemming from the application of the proposed methodology to the *Araraquara* substation are encouraging. Notably, we have demonstrated adept photo capture, georeferencing, and seamless integration within the Virtual Reality (VR) realm. Users were able to immerse themselves in a virtual environment, benefitting from detailed navigation capabilities and location-specific insights via interactive 360-degree photos.

The process of updating the database with new photos has proven to be expedient for engineering decisions, facilitating swift responses to accidents, unforeseen events, and complications within the substation. This dynamic capability empowers engineers by furnishing immediate insights upon the addition of a new photo, underscoring the practical utility of the methodology.

To bolster precision, a survey leveraging drone-captured orthomosaic imagery was conducted, yielding high-resolution images that offer enhanced details on the electromechanical connections and assemblies of substation assets.

The implemented system harnesses the potential of orthomosaic imagery, featuring a layered system that grants users control over its visualization and transparency, thereby enhancing usability.

While the integration of georeferenced photos represents a notable milestone, ongoing development efforts are concentrated on fine-tuning the pattern recognition algorithm and addressing identified challenges. Looking ahead, the proposed methodology holds promise for aiding the energy industry in managing and maintaining critical infrastructures, thereby fostering safety, efficiency, and innovation in the electric power sector.

5. CONCLUSION

The integration of geospatial technologies, spanning GIS systems, CAD, 360-degree images, and drone imagery, presents transformative potential, offering a comprehensive and efficient portrayal of environments across diverse applications. Despite encountered challenges, our proposed methodology aimed at enhancing navigation and interaction within virtual electrical substations has yielded promising outcomes, fostering improvements in operational efficiency, safety, and innovation.

This study introduces a novel methodology for virtual navigation and interaction within electrical substations, leveraging georeferenced 360-degree photos within a 3D virtual environment. Preliminary results from its application to the *Araraquara* substation exhibit successful photo capture, georeferencing, and seamless integration within the Virtual Reality (VR) domain. Users can immerse themselves in a virtual environment, accessing detailed navigation capabilities and location-specific insights through interactive 360-degree photos.

The update process, involving the addition of new photos to the database, has proven satisfactory for engineering decisions, facilitating swift responses to accidents, unforeseen events, and operational complexities within substations. This dynamic capability empowers engineers by furnishing immediate insights following the addition of a new photo, underscoring the practical utility of the methodology. While the integration of georeferenced photos represents a significant milestone, ongoing development efforts are directed towards refining the pattern recognition algorithm.

Looking forward, our proposed methodology holds considerable promise for assisting the energy industry in managing and maintaining critical infrastructures. By amalgamating georeferenced photos with virtual navigation, our approach aims to augment safety, efficiency, and innovation within the electric power sector. The evolution of this approach signifies a pivotal stride towards a more immersive and efficacious paradigm in energy system management. Continuous exploration and enhancement of integrated technologies, as previously discussed, further enrich our capabilities to comprehend and intervene in the surrounding world.

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