A Study on Creating Digital Twin Foliage Representation Through Computer Vision, Aerial Image Analysis and Machine Learning techniques to enhance the Network Planning and Deployment

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ABSTRACT

Digital Twin Representation of Foliage

The demand for higher bandwidth, throughput, and reduced latency, propelled by connected devices, has spurred millimeter-wave (mmW) network development critical for 5G realization. Despite challenges like scattering, atmospheric absorption, and foliage impact, this study proposes a cost-effective solution. By integrating Google Street View and satellite images with computer vision and machine learning, it aims to enhance mmW network planning. The approach facilitates strategic node placement for optimal coverage and user experience. Additionally, the study underscores the importance of foliage in mmW networks, particularly focusing on foliage presence and tree height estimation using Google Street View and satellite images, paving the way for more efficient network deployment and management.

PROBLEM AND PURPOSE STATEMENT

The study aims to develop an advanced digital twin mirroring the physical environment, emphasizing detailed foliage information critical for high-frequency mmW network planning. By integrating machine learning and computer vision, the model will accurately identify and categorize foliage in images, enabling pixel-level analysis for a comprehensive understanding of vegetative elements. Through validation using aerial and street view imagery alongside LiDAR or UAV datasets, the model's accuracy will be assessed using grid-based evaluations and Mean Intersection over Union (MIoU) metrics. This approach bridges theoretical network planning with practical challenges, enhancing network operators' ability to optimize performance in environments affected by foliage.

RESEARCH QUESTIONS

RQ1

What extent can a digital twin representation of foliage, created using machine learning, computer vision, and image analysis techniques achieving an MIoU greater than 60% with LiDAR as the ground truth, effectively capture the spatial distribution and characteristics of foliage in natural environments?

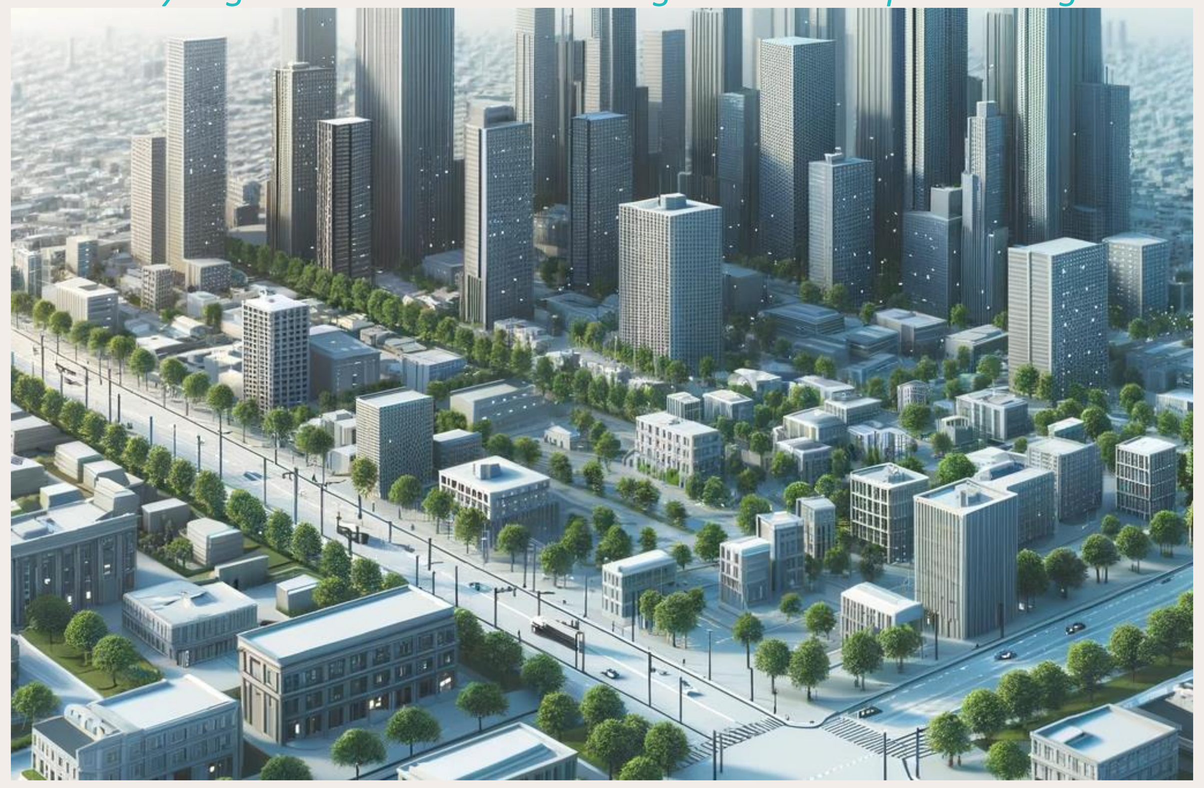
RQ2

What is the cost difference in obtaining foliage information using the integration of image analysis from street view and aerial view images with computer vision techniques compared to traditional survey methods like LiDAR or UAV?

RQ3

How can digital twin models incorporating foliage representation contribute to more effective wireless network optimization in smart city environments by identifying suitable node placements?

Smart City Digital Twin: Urban Planning and Green Spaces Integration

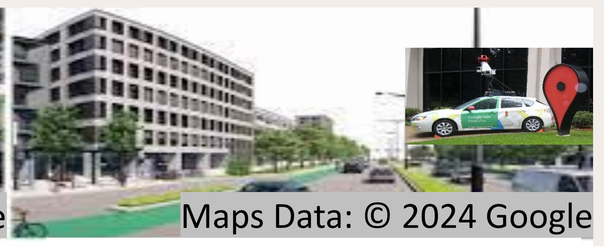


Note. This image was generated with the assistance of Artificial Intelligence (AI).

MATERIAL & METHODS

Google Aerial and Satellite view images

(a) Aerial perspective

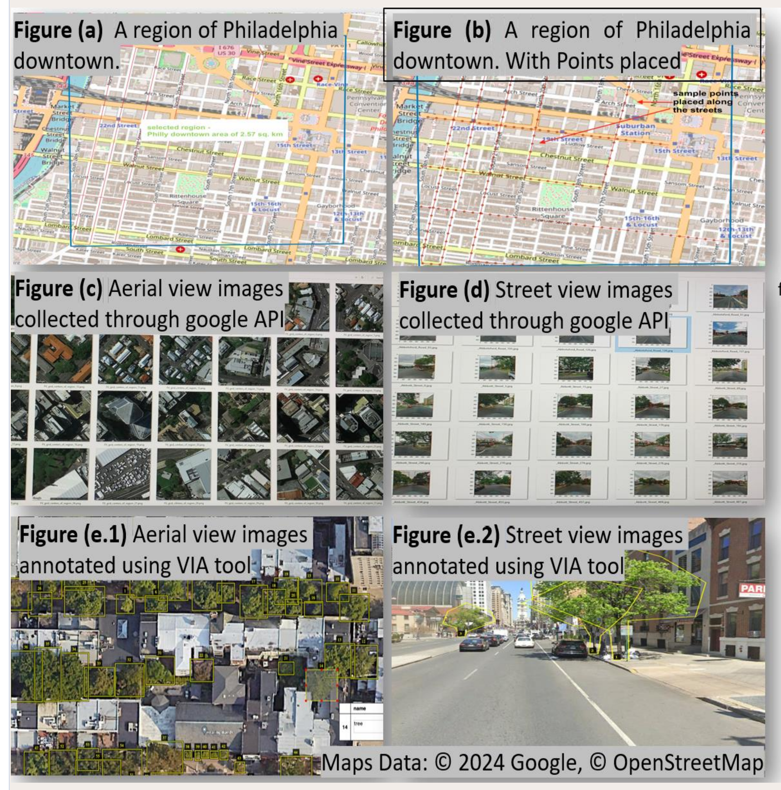


(b) Street view perspective

- Imagery Sources: High-resolution Google Street View and aerial images (Google for Developers Maps Static API, n.d.; Google for Developers Street View Static API Overview, n.d.).
- Google Maps API for collecting street views and aerial imagery (Google for Developers Maps Static API, n.d.; Google for Developers Street View Static API Overview, n.d.).
- LiDAR and UAV datasets for benchmarking and validation purposes (OCM Partners, 2024; Philadelphia Lidar - LAS Files 2022 {2022} - Big Ten Academic Alliance Geoportal, 2022).
- Machine Learning Tools: Software libraries, Neural Network models for developing instance segmentation models, image processing (e.g., TensorFlow, PyTorch with Mask R-CNN).
- GIS Software: For spatial analysis and comparison with traditional data sources. (e.g., Quantum Geographic Information System (QGIS) (QGIS Development Team, 2021), Google Earth engine for data analysis and mapping).

Research Design Methods

- **Data Preprocessing:**
  - Verify foliage representation, remove duplicates/artifacts, clean images.
  - Use hxw (ex. 640x640) pixels and standard channels to standardize data.
- **Image Feature Extraction:**
  - Extract color, texture, shape from foliage using image processing.
  - Use PCA for large datasets to reduce feature vector dimensionality.
- **Machine Learning Model Training:**
  - Train a mask RCNN model to identify and segment foliage.
  - Split dataset: 80% training, 20% validation. Fine-tune for accuracy.
- **Model Evaluation:**
  - Use unseen testing dataset for unbiased model evaluation.
  - Assess model with accuracy, precision, recall, F1, IoU, ROC curves.
- **Data Fusion and Integration:**
  - Merge aerial/street view images for a complete digital twin.
  - Integrate different perspectives for a comprehensive environment view.
- **Spatial Analysis:**
  - Conduct geospatial analysis, clustering to map foliage distribution.
- **Temporal Analysis:**
  - Analyze changes in foliage over time for ecological insights.
- **Machine Learning Interpretability:**
  - Make model decisions interpretable via feature visualization, saliency maps.
- **GIS Integration:**
  - Combine foliage data with GIS for advanced spatial analyses.
- **Visualization and Reporting:**
  - Use maps, charts, graphs to communicate findings to stakeholders.
  - Summarize key insights in reports for decision-makers, researchers.
- **Iterative Process:**
  - Revisit steps to refine digital twin quality as insights evolve.
- **Validation and Testing:**
  - Validate and test the digital twin to ensure environmental accuracy.
- **Comparison with LiDAR or UAV Data:**
  - Compare digital twin foliage measurements with LiDAR/UAV datasets.
  - Partition study area into grids for detailed comparisons.
  - Visualize data intersection using Venn diagrams for clarity.



Research Design

Data Collection Strategy

(a) Select the region of interest for the creation of a digital twin for foliage.

(b) Create a 640x640 pixel grid with center point and latitude/longitude for the area of interest along the streets using Quantum Geographic Information systems (QGIS).

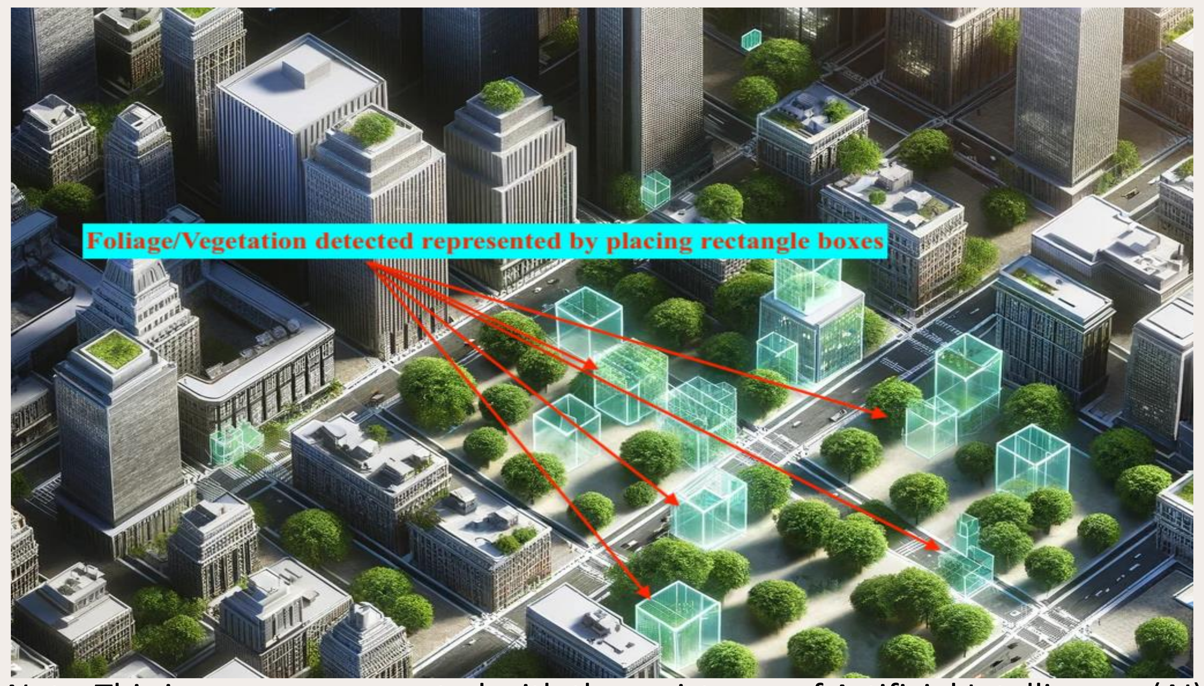
(c) Using the Google staticmap API, collect aerial view images along these points.

(d) Using the Google Street View static API, collect street view images along these lines.

(e.1, e.2) To train the machine-learning model, add annotations to images with the VGG Image Annotator (VIA).

RESULTS

Digital Twin Representation of Foliage - Example



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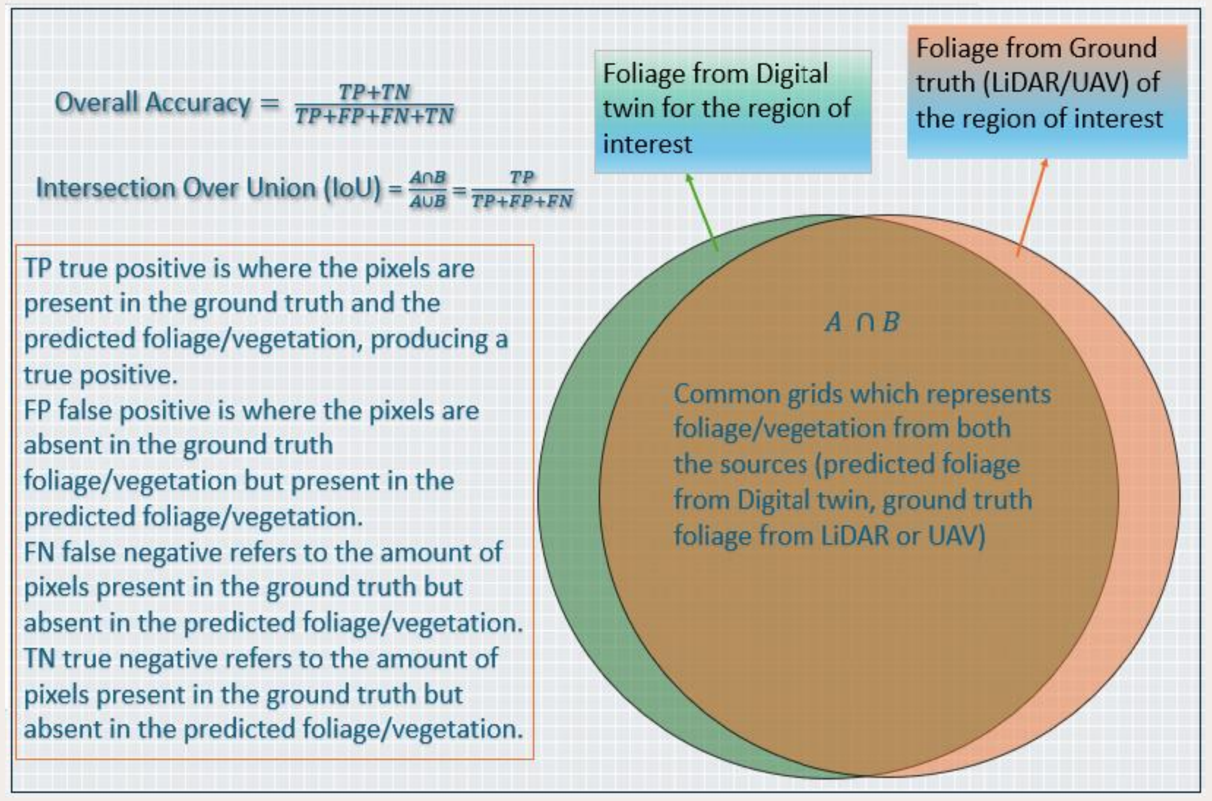
Digital Twin Representation of Foliage measurement Criteria



Original image

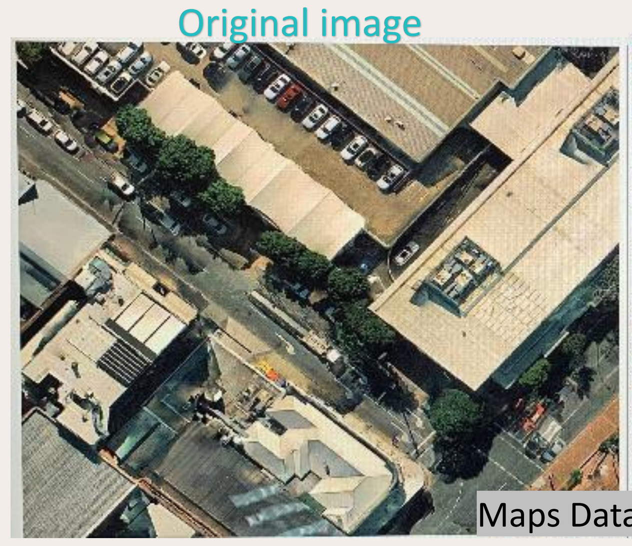
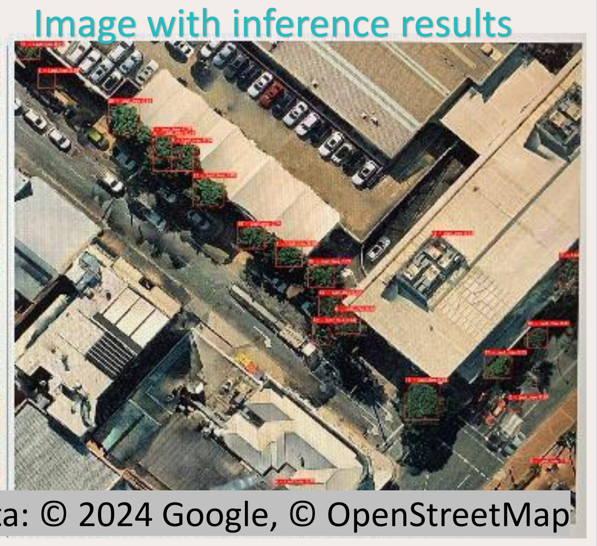
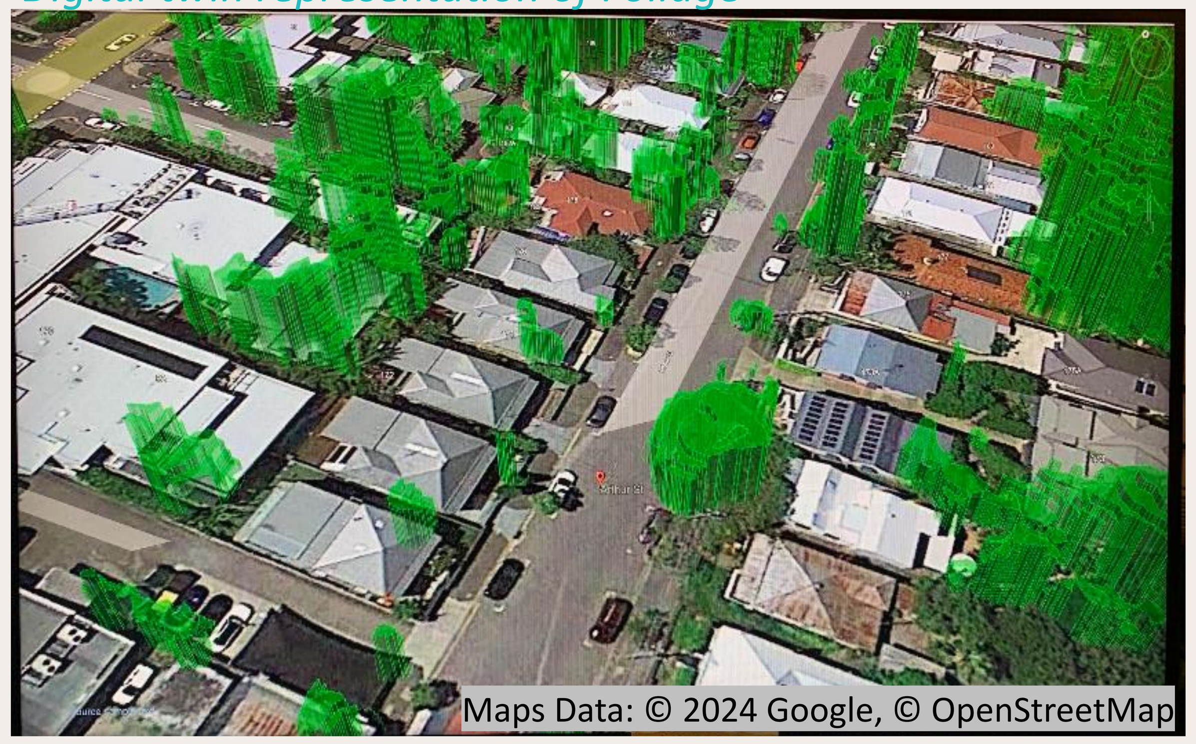


Image with inference results



Digital twin representation of Foliage



CONCLUSIONS

Digital twins significantly advance over traditional methods like LiDAR and UAVs in urban and city planning. By automating foliage detection and analysis, digital twin representation enables swift and accurate data collection, facilitating more efficient network planning, urban development, and other applications. The impetus behind developing a digital twin representation of foliage arises from the escalating demand for precise and current foliage information across diverse sectors, encompassing telecommunications, urban planning, and environmental conservation. Industry reports and white papers underscore the critical role of digital twin technology in optimizing telecommunications infrastructure and enhancing service quality (Alkhateeb et al., 2023; Khan et al., 2022; Kuruvatti et al., 2022). Additionally, government initiatives aimed at sustainable urbanization and environmental stewardship emphasize the value of digital twins in informing data-driven decision-making processes (Angin et al., 2020; T. Deng et al., 2021; Mylonas et al., 2021; Shahat et al., 2021). The Digital Twin can be extended to accommodate street furniture, building facades for future.

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Note: Due to space only, few references listed. More references available on request.

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