Mesh-Based Tunnel Geometry Modeling and Sensor Simulation for Infrastructure Inspection

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SUMMARY

Tunnels are critical infrastructure used in transportation, construction, and utilities. Geometric tunnel models support diverse applications including structural health monitoring and safety assessment, maintenance planning and resource optimization, design validation and construction quality control, and autonomous inspection and robotic deployment. Furthermore, simulating different sensor types within realistic tunnel models is essential for optimizing sensor configurations and significantly reducing the cost and time required for field data collection.

However, acquiring tunnel geometry data presents significant challenges: unstructured natural tunnels often lack design drawings and BIM models; traditional total station point measurements are insufficient to capture complex geometric structures; and terrestrial laser scanning suffers from occlusion, resulting in scanning data gaps. Mobile Laser Scanning (MLS) technology, with its efficiency and flexibility, enables continuous acquisition of complete tunnel data. However, MLS data faces challenges such as SLAM drift errors and point cloud noise.

To address these challenges, a systematic modeling framework is proposed: first, total station control points are used to minimize MLS drift errors; then, point cloud filtering and segmentation techniques are applied to handle noise; finally, a triangular mesh tunnel model is constructed from the processed point cloud. Based on this triangular mesh model and ray tracing algorithms on the mesh, simulation models for terrestrial laser scanners and low-cost LiDAR are established to simulate data acquisition of different sensors in tunnels. This approach reduces the difficulty and cost of actual data collection and enables early sensor model selection. Additionally, robot motion models can be deployed in the tunnel mesh model using Gazebo, providing a foundation for validating automated tunnel maintenance of digital twins.