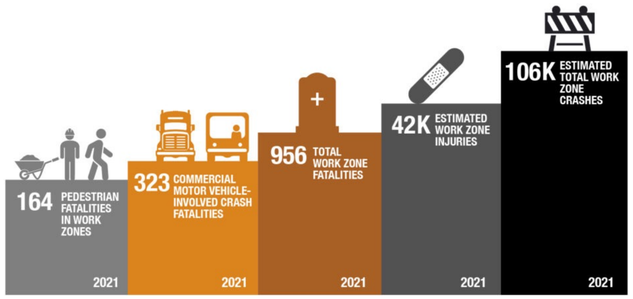
Leveraging Vehicle Sensors to Digital Twin for Work Zone Safety and Optimization

Hangyu Li, Keke Long, Zhaohui Liang, Chengyuan Ma, Bofeng Cao, Zheng Li, Xiaopeng Li
Civil & Environmental Engineering, University of Wisconsin-Madison

Background

Work zones present unique challenges for traffic management and safety. Unexpected driving environments such as changes in road topology, detours, and dynamic speed limits can significantly increase safety risks. **Poor layout and low-quality** (deformed, damaged, faded, etc.) signs and barrels, drums, and cones further deteriorate traffic safety. The existing practice of work zone setting and inspection relies on **manual work**, which may involve **safety risks** and **human errors** and greatly limits the extent of safe work zones that can be carried out. These challenges are particularly pronounced as state DOTs grapple with absorbing the **new MUTCD updates** before mid-2025. The associated costs and inefficiencies of organizing training and adapting professionals to these changes further underscore the need for innovation.

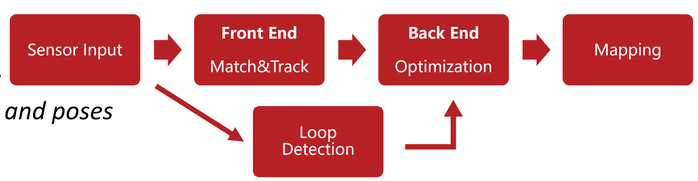


Objectives

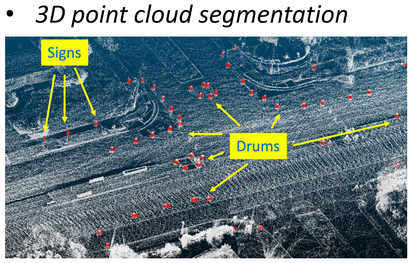
- Create a high-fidelity **digital twin** of work zones using **vehicle sensors** (camera-captured videos, LiDAR point clouds, and GNSS locations);
- Utilize this digital twin to **assess the compliance and safety of work zone setups**, including the layout and quality of cones, barriers, signs, etc.

Method

- **Simultaneous Localization and Mapping (SLAM)**
  - *Build a map for the environment;*
  - *Self-localize in unknown places;*
  - *GNSS-aided LiDAR-Inertial Odometry (LIO);*
  - *Generate dense point clouds and locations and poses of the vehicle.*



- **Object Detection**
  - *3D point cloud segmentation*



✓ Feature-based
✓ Reflectivity
✓ Pre-defined shape

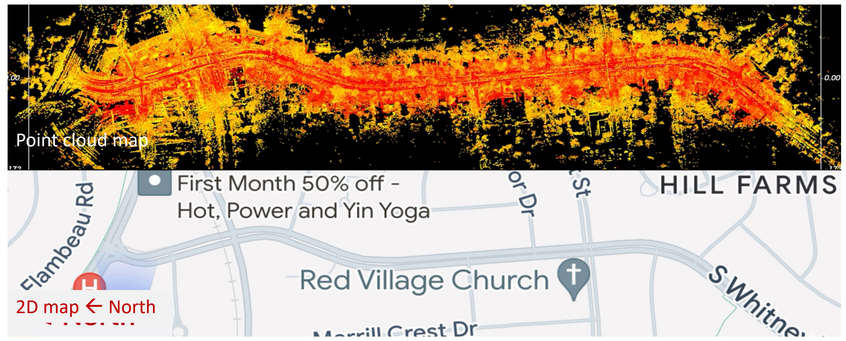
  - *2D image detection*

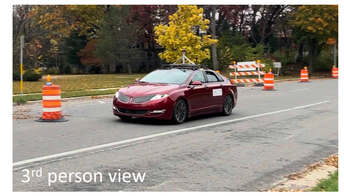
✓ Learning-based
✓ YOLO for detection
✓ CNN for quality check

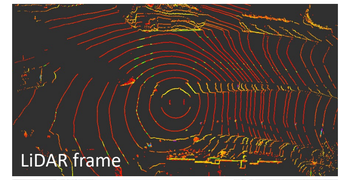
- **Hybrid Compliance and Quality Check**
  - *Automated evaluation with predefined rules + Experience-based manual review*
  - *For spacing, placement, visibility, etc.*

Experiment

- We conducted our experiment on N Whitney Way, Madison, WI.
- Our vehicle is equipped with a LiDAR and a front-view camera.
- The vehicle cruised through a work zone on a regular road.
- Sensor data was recorded synchronically.
- A dense point cloud map is generated in real-time.

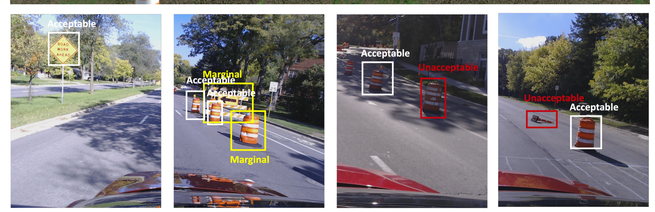






Results

- **Digital Twin**
  - *Dense point cloud map as background*
  - *3D object detection for locations and poses*
  - *Pre-built digital assets (devices, poles, signs)*
  - *Multi-perspective reconstruction*
  - *Game-engine- and simulator-ready*
- **Quality evaluation**
  - *Learning-based image recognition*
  - *Data-driven automatic evaluation*
  - *Experience-based manual annotation*
  - *Alignment marking in digital twin*
  - *Continuous learning with accumulated data*
- **Compliance check**
  - *Human-friendly BEV interface*
  - *Rule-based automated initial detection*
  - *Manual detailed problem annotation*
  - *Minimum-effort handling optimization*
  - *Result illustration in digital twin*



Future Potentials

- Neural radiation field (NeRF) and 3D Gaussian Splatting (3DGS) could be further employed with LIVO to refine the details of digital twins and restore high-fidelity 3D models;
- The digital twin can be shared with other road users through V2X technology to improve expectations and thus enhance road safety, e.g., cooperative guide through work zones;
- Large VLM models can be trained to understand region-specific rules and automatically evaluate work zone setups and check compliance through multimodal inputs.