RESEARCH SEMINAR · NOVEMBER 2026

Resilient Intelligent Infrastructure: Perception, Robots, and Auditable Decisions Across Scales

Connecting Physics-Grounded Field Robotics, Cooperative Roadside LiDAR, and Source-Traced Geospatial AI with Public Agencies

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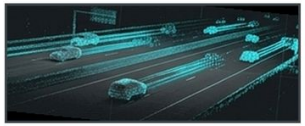
bshang@umd.edu · https://cnpcshangbo.github.io/

How Can the Built Environment Perceive Itself Across Scales?

Core Question: At every spatial scale—from a steel bridge girder (~m) to an urban intersection (~100 m), a highway corridor (~km), and a city network—what can be observed, where do sensors fail, and what decisions become auditable?

MACRO

~ km



InfraLiDAR-Eval

Continuous traffic monitoring with fixed roadside LiDAR

61.9-hour dataset · failure analysis

MESO

~ 100 m



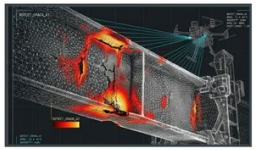
PACO

Cooperative observability at urban intersections

0.37 (ADAS) · 0.61 (AV) · 1.00 (V2I)

MICRO

~ m



Embodied Robotics

UAVs and climbing robots assess physical integrity

BIRDS · concrete defect detection

Three scales, one model — a unified, multi-scale picture of the built environment

City & Network Synthesis (UMD M-TRAIL): Fixed sensors provide persistent macro/meso observability; embodied robots provide micro-scale physical access; CERRA + LLM-SUMO + feasibility-preserving optimization turn evidence into agency decisions.

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From Physics-Grounded Flight Control to Multi-Scale Infrastructure AI

1. Ph.D. & UC Merced

2013 – 2020

- Fractional-order UAV visual servoing (Nonlinear Dynamics '19)
- Sampling-period margin analysis (ASME '17)
- SmartCaveDrone 3D mapping (ICUAS '17)

2. Missouri S&T Postdoc

2020 – 2022

- BIRDS flying + clamping bridge robot
- U.S. Patent 12,296,994 B2 ('25)
- ASCE 2025 Pankow Award team
- INSPIRE & PHMSA reports

3. CCNY / CUNY Postdoc

2022 – 2026

- Concrete defect robot + 3D mesh (IEEE T-ASE '25 / IROS '25)
- PACO & safety auditing (CVPRW '26, MobiSPC '25)
- Freight GSV AI (IEEE OJ-ITS '26)

4. UMD M-TRAIL Postdoc

Jul 2026 – Present

- Build & operate CERRA geospatial AI platform
- Integrate LLM-SUMO digital twin (Oct '26)
- PAR auditability standard & IBM Heron VRP validation

Talk Roadmap

Part I: Micro-Scale (~m) — Fractional-Order UAV Control, BIRDS Flying-Clamping Robot, & CCNY Concrete Defect Analytics
Part II: Meso-Scale (~100 m) — PACO Cooperative Observability (0.37 / 0.61 / 1.00) & CVPRW '26 Safety Auditing
Part III & IV: Macro (~km) & City Scale — InfraLiDAR-Eval (61.9 h), IEEE OJ-ITS Freight, CERRA, LLM-SUMO & Quantum VRP · Part V: 5-Year Agenda & Teaching

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PART I · MICRO-SCALE (~ M)

Physics-Grounded Control & Embodied Inspection Robots

Operating under bridges, near concrete columns, and on steel girders where GPS is denied, sampling periods fluctuate, and inspectors need quantitative 3D evidence.

0.933 s vs 0.546 s

Max stable vision sampling period: FOPD vs. IOPID (+71%)

U.S. Pat. 12,296,994

BIRDS flight + surface-traverse bridge robot (ASCE Pankow '25)

IEEE T-ASE / IROS '25

Concrete defect robot, AWS CNN & 3D mesh localization

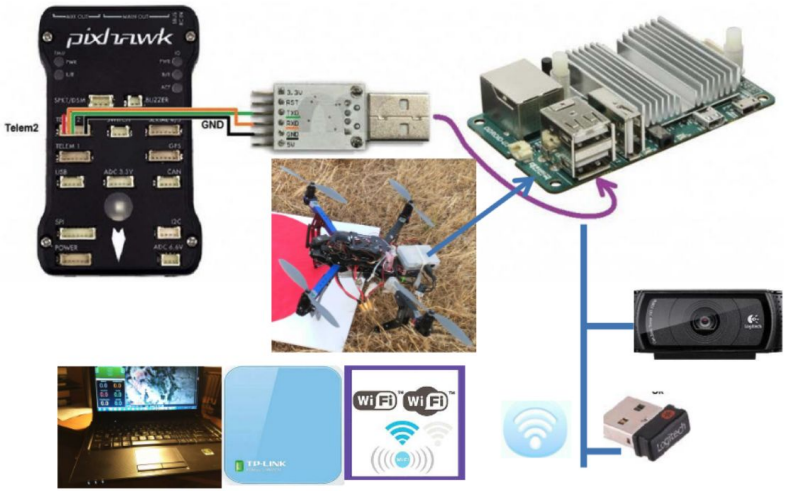
Fractional-Order Visual Servoing Control of Quadrotor UAS

Why Visual Servoing Breaks Near Structures

• Under-bridge flight denies GPS and introduces aerodynamic turbulence & wind gusts.
• Onboard vision processing creates larger, variable sampling periods that destabilize integer-order PID loops.
• Target loss from camera FOV causes immediate mission failure.

Iso-Damping Fractional-Order Design (FOPD)

• Extends derivative/integral action to real orders (λ, μ), enforcing zero phase slope at gain crossover: $d \arg G(j\omega)/d\omega = 0$.
• Built reproducible Simscape & OS4 benchmarks plus custom Pixhawk + embedded Linux + ground HSV tuning stack.
• Extended to RGB-D cave SLAM in SmartCaveDrone (ICUAS '17).



Experimental Quadrotor Visual Servoing Architecture (Pixhawk + Odroid Linux + Ground HSV Calibration)

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Sampling-Period Tolerance & Gain-Invariance Under Vision Latency

0.933 s vs. 0.546 s (+71%)

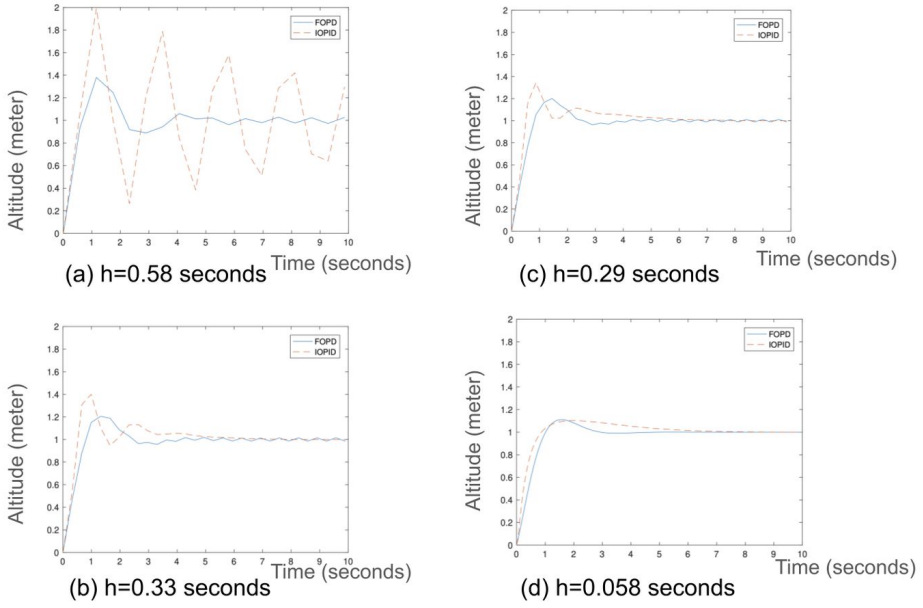
Maximum stable sampling period achieved by FOPD vs. integer-order PID (ASME IDETC 2017), tolerating lower-rate onboard vision.

20% Flight Error Reduction

Outdoor/indoor precision hovering experiments showed 20% lower tracking error and flatter ITAE growth across sampling periods.

Design Principle Carried Forward

Sampling period, sensor geometry, and actuation margin are explicit design inputs—not noise to be averaged away downstream.



Step Response Across Sampling Periods h = 0.058 s to 0.58 s: IOPID Oscillates at 0.58 s While FOPD Stays Damped

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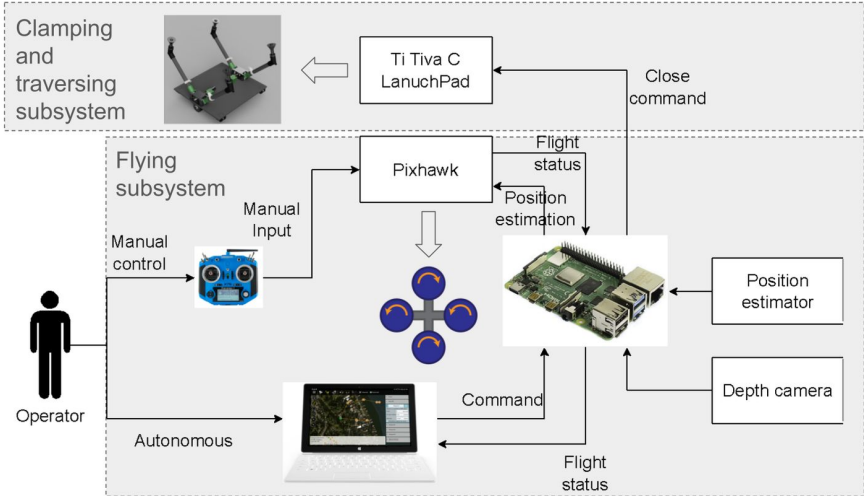
BIRDS: Hybrid Flying & Surface-Traversing Bridge Inspection Robot

Operational Motivation & System Concept

• 42% of U.S. bridges are 50+ years old; snooper trucks block lanes and free-flying UAVs drain batteries fighting under-deck wind.
• BIRDS flies into position, clamps onto an I-girder bottom flange, shuts down rotors, and wheels along the beam for close-range sensing.

Patented Hardware & National Recognition

• Co-inventor: U.S. Patent 12,296,994 B2 (granted May 2025).
• Selected for the ASCE 2025 Charles Pankow Award for Innovation (Missouri S&T, PI: Prof. Genda Chen).
• Documented in INSPIRE-024 Final Report (2024) & PHMSA CAAP Pipeline Robotics Report (2022).



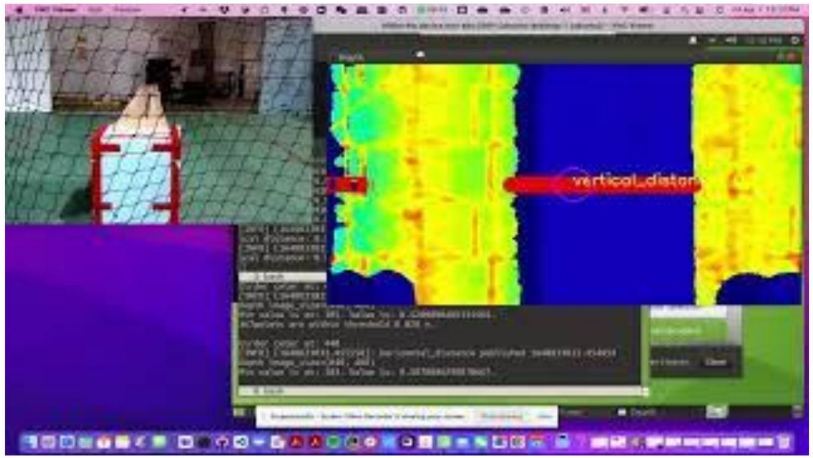
BIRDS Dual-Subsystem Architecture: Pixhawk + Onboard Depth Vision + TI Tiva-C Clamping & Traversal Controller

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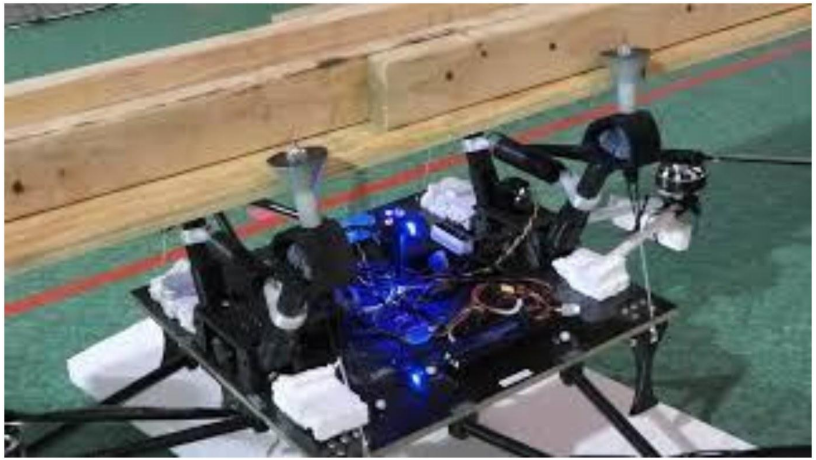
Non-GPS Girder Detection, Asymmetric Clamping & Flange Traversal

Edge Guidance & Perching Mechanics (ROS · NVIDIA Jetson · Raspberry Pi)

• RGB-D Girder Perception: Segments steel I-girder flange edges, centerline, heading, and vertical clearance onboard without GPS; paired with CFD ceiling-effect analysis (IWSHM '21).
• Safety-Asymmetric Clamping: Closes in 1.3 s upon reaching contact clearance threshold to secure attachment under wind sway, with 8.5 s controlled release and wheeled flange traversal.



RGB-D Girder Detection · ▸ https://youtu.be/wXONyFR4gCQ



Clamped Flange Traversal · ▸ https://youtu.be/WLU0VSCrnQs

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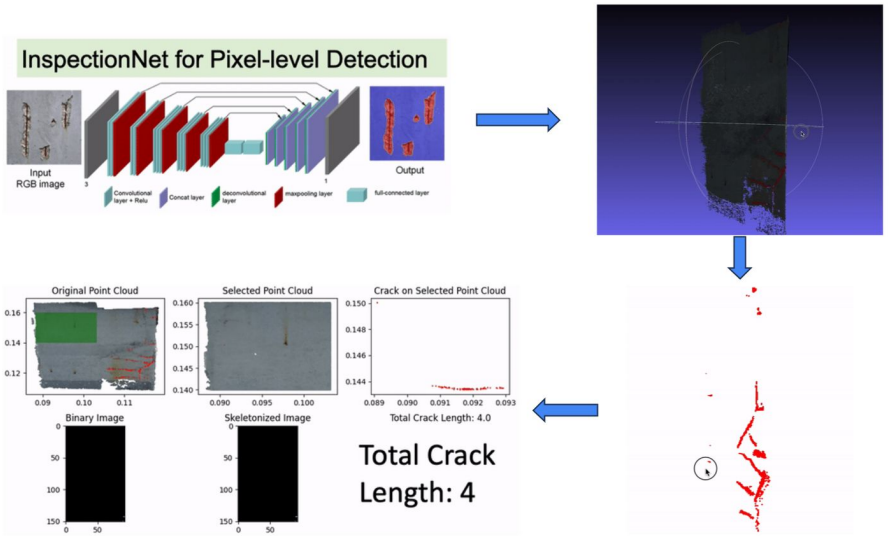
Robotic Inspection & 3D Structural Defect Localization

Separate CUNY Climbing-Robot Workflow

• Developed at CCNY Robotics Lab (with J. Feng & Prof. J. Xiao)—distinct robot and codebase from BIRDS.
• Built custom iOS operator app for climbing-robot control and live field inspection review.
• Streams imagery to AWS for pixel-level CNN segmentation of cracks, spalling, and stains.

From 2D Masks to Metric 3D Geometry

• Registers segmented defects onto WebODM 3D point clouds and meshes.
• Skeletonizes crack topology to compute physical crack length and location in structural coordinates.
• Published in IEEE T-ASE (2025) & presented at IEEE IROS 2025.



InspectionNet Pixel Detection → 3D Point-Cloud Registration → Skeletonized Metric Crack Length

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Structure-Scale 3D Defect Mapping & Multimodal NDT Synthesis

Solving the 'Thousand-Image' Bottleneck

• Raw drone/robot surveys generate thousands of overlapping close-up photos that inspectors cannot audit frame by frame.
• Projecting segmented cracks (red) onto a full 3D bridge-column mesh preserves structural context for cycle-over-cycle comparison.

Complementary Multimodal NDT Record

• Thermal IR: Code-specified passive vs. active thermography for RC deck delamination (J. Civil Struct. Health Monit., 2025).
• Acoustic Impact-Echo: Contrastive learning for concrete slab defect mapping (Constr. Build. Mater., 2025).
• Aerial NDT&E synthesis (Materials Evaluation, 2023).



Full-Scale 3D Bridge Column Mesh with Localized Crack Network Overlay

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PART II · MESO-SCALE (~ 100 M)

Cooperative Intersection Observability & VRU Safety

Quantifying why vehicle-mounted sensors hit a hard geometric occlusion ceiling in urban intersections—and building auditable roadside LiDAR intelligence.

0.37 → 0.61 → 1.00

PACO scene observability: 120° ADAS vs. 360° AV vs. Roadside V2I

40,793 Frames

68 min of real multi-class NYC trajectories at 10 Hz

n = 180 Near-Misses

Auditable zero-margin conflict mapping (CVPRW DriveX '26)

NYC Urban Intersection Testbed & Cross-Configuration Portability

24/7 Multimodal Intersection Deployment

• Signalized NYC testbed (Convent Ave & W 141st St) equipped with elevated 128-beam Ouster OS1-128 LiDAR, pan-tilt RGB camera, and edge GPU unit.
• Captures unoccluded oblique 3D trajectories of vehicles, cyclists, and pedestrians unaffected by nighttime glare or shadows.

Sensor Synchronization & Beam-Count Scaling

• Engineered clock-drift synchronization, 2D–3D extrinsic calibration, background subtraction, and site-portable config layers.
• Quantified how LiDAR beam count (128 → sparser units) governs VRU detection recall (MobiSPC '25; U.S. DOT Report DOT 91974).



Elevated Ouster OS1-128 LiDAR, Ground-Truth Camera & Edge GPU Box in NYC

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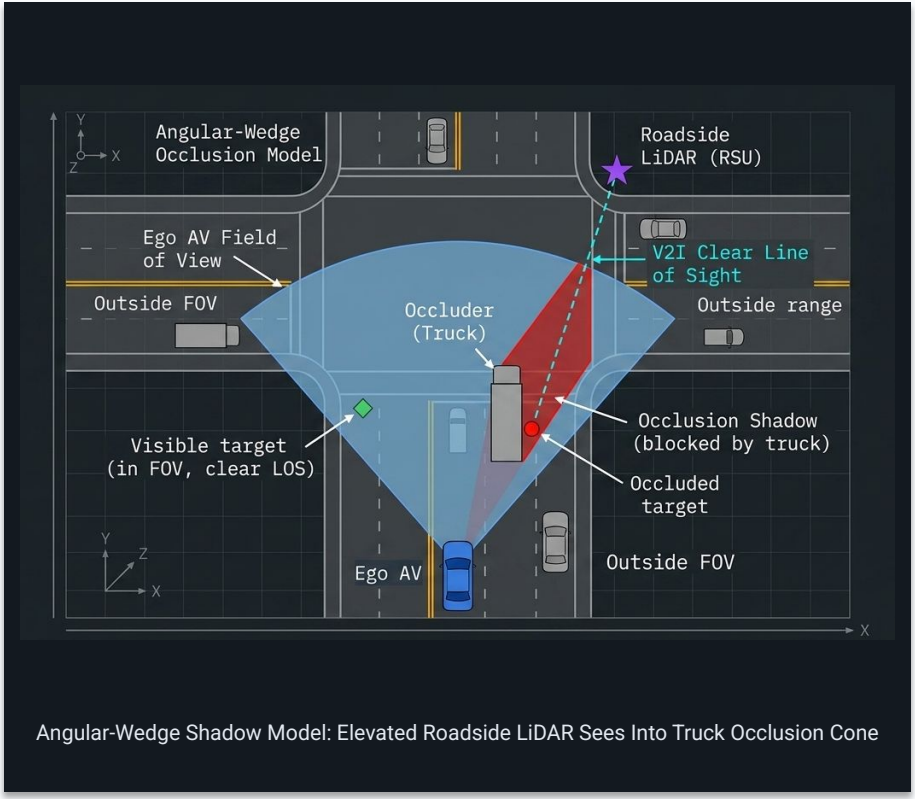
PACO: Parametric Assessment of Cooperative Observability

5-Stage Parametric Evaluation Pipeline

1. Ego Instantiation: Place virtual onboard sensors on real vehicle trajectories.
2. Sensor Coverage: Compute parametric horizontal FOV & range sectors.
3. Occlusion Resolution: Ray-tracing-free angular-wedge shadow model.
4. Cooperative Augmentation: Fuse ego + elevated roadside V2I LOS.
5. Multi-Scope Metrics: Scene-wide vs. active conflict-partner recall.

Empirical Trajectory Foundation

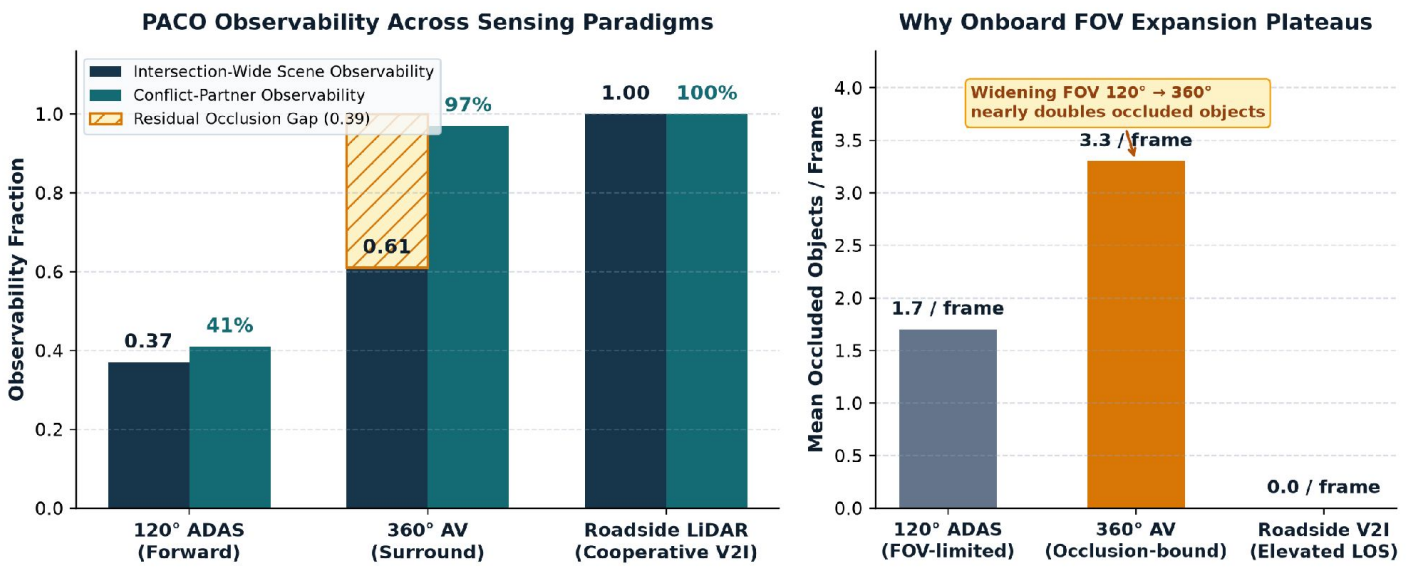
• Driven by 68 minutes (40,793 frames at 10 Hz) of dense multi-class NYC intersection trajectories.
• Evaluates exact line-of-sight geometry rather than synthetic empty-road assumptions.
• Accepted at TRB Annual Meeting; in prep for IEEE T-ITS.



Angular-Wedge Shadow Model: Elevated Roadside LiDAR Sees Into Truck Occlusion Cone

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The Observability Gap: Occlusion—Not FOV—Is the Binding Constraint



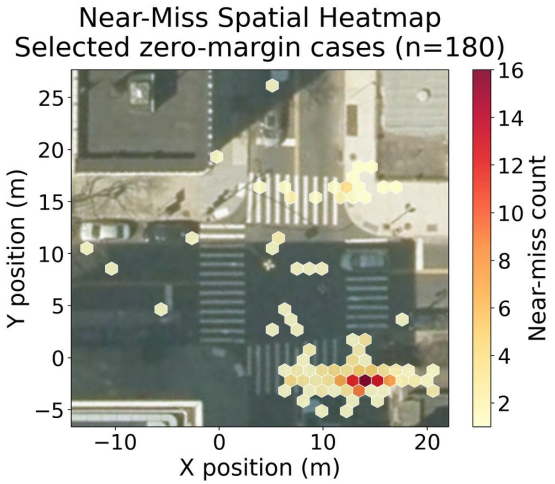
Mathematical Necessity of Infrastructure Sensing: Expanding vehicle FOV from 120° ADAS (0.37) to 360° AV (0.61) still leaves 39% of the intersection scene unobservable—and occluded objects double from 1.7 to 3.3 per frame. Only elevated V2I LiDAR closes the gap to 1.00.

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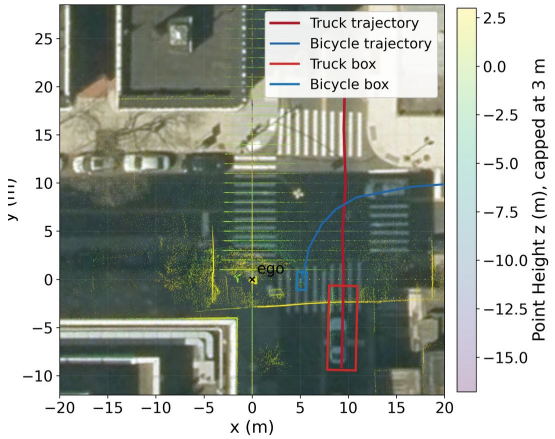
Auditable Cooperative Safety Auditing at Urban Intersections

From Raw Point Clouds to Auditable Near-Miss Evidence

• Stabilizes fine-tuned CenterPoint 3D tracks with dynamics-aware Kalman smoothing and human-in-the-loop QA to audit cooperative V2X safety.
• Isolates n = 180 zero-margin near-miss events at crosswalk/turn hotspots; distinguishes benign lateral proximity from sub-second longitudinal collision risk (TTC ~ 1.08 s valley in heavy-truck vs. bicycle conflict).



Near-Miss Spatial Heatmap (n = 180 Zero-Margin Conflicts)



Heavy-Truck vs. Bicycle Trajectory & TTC Audit Case

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PART III · MACRO-SCALE (~ KM)

Continuous Highway Sensing & Scalable Urban Freight

Why moving-vehicle benchmarks fail on stationary elevated highway sensors—and how domain-specific LiDAR and Street View pipelines scale across corridors.

90.1% vs. 72.9%

I-95 crossing recovery: fixed-sensor pipeline vs. ego detector

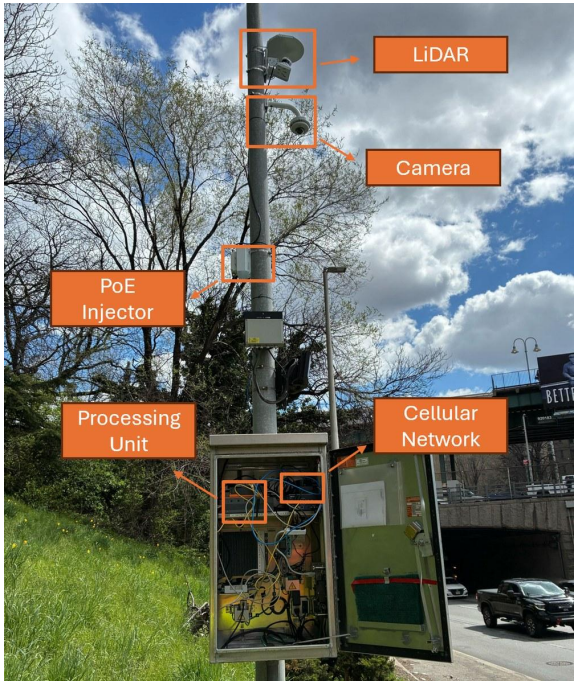
61.9 Hours

InfraLiDAR-Eval continuous dataset across 743 raw sessions

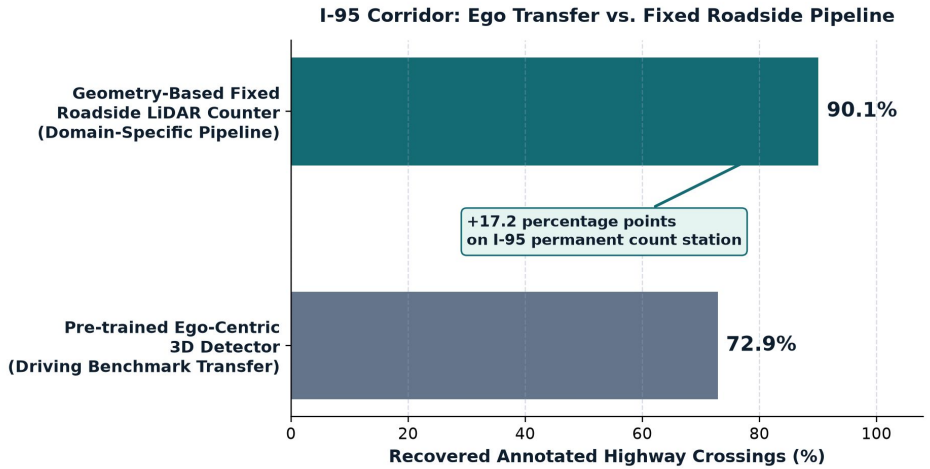
IEEE OJ-ITS 2026

City-scale fine-grained truck sensing from Street View + VLMs

Why Ego-Centric Driving Benchmarks Do Not Transfer to Fixed Highway LiDAR



NYSDOT I-95 @ Jerome Ave (Bronx)
Fixed LiDAR + Camera + Edge + Cellular



The Viewpoint Domain Gap (I-95 Permanent Count Station)

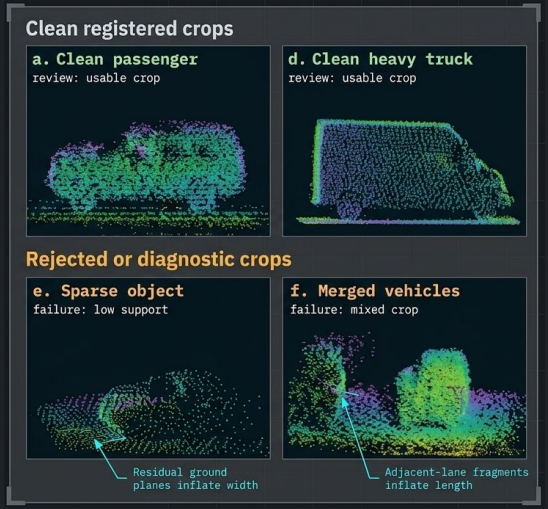
- Ego-centric benchmarks (Waymo, nuScenes) assume ground-level horizontal scans.
- Under elevated oblique highway viewing, a pre-trained ego detector recovered only 72.9% of annotated crossings vs. 90.1% for our geometry-based roadside pipeline.

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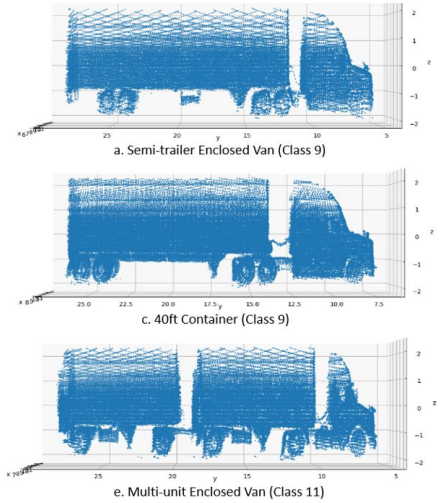
InfraLiDAR-Eval: 61.9-Hour Pipeline & Roadside Failure Taxonomy

4-Stage End-to-End Architecture Across 61.9 Hours (743 Raw Roadside Sessions)

1. Raw Ingestion (lane ROIs & crossing lines) → 2. Filtering (strict 0.10 m ground clearance & seeded DBSCAN) → 3. Cross-Lane Arbitration (trajectory linking & duplicate suppression) → 4. Sparse-to-Dense FilterReg Multi-Frame Registration.



Failure Analysis: Residual Ground Planes, Sparse Support & Merged Crops



Multi-Frame Registered FHWA Class 9 & 11 Trucks

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Drive-By Urban Freight Sensing & Training-Free VLM Classification

Drive-By Urban Freight Sensing (IEEE OJ-ITS 2026)

• Fixed sensors cover key corridors, but freight planners also need city-wide curb and arterial truck distributions without installing hardware on every block.

• Developed a deep-learning pipeline for large-scale, fine-grained truck body classification from Google Street View imagery.

• Turns opportunistic street-level imagery into scalable freight exposure maps across urban neighborhoods (open access, Sept 2026).

Bridging the LiDAR Modality Gap with VLMs

• Re-annotating 3D bounding boxes and FHWA truck classes for every new roadside LiDAR geometry is a major deployment bottleneck.

• Co-developed training-free and few-shot Vision-Language Model (VLM) frameworks (arXiv:2602.09425; TRB 2026) that project 3D roadside point clouds into structured visual views.

• Enables zero/few-shot vehicle & truck classification across new sensor configurations.

Macro-Scale Synthesis

Combines high-frequency 24/7 corridor depth on highways (InfraLiDAR-Eval) with city-wide spatial breadth (Street View freight sensing) and low-annotation cross-site transfer (VLM point-cloud classification).

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PART IV · CITY & NETWORK SCALE (UMD M-TRAIL)

CERRA Platform, Traffic Digital Twins & Auditable Decisions

Closing the engineering bottleneck between spatial infrastructure data and agency action—where every AI-assisted study carries traceable sources and physical feasibility guarantees.

cerra.cloud

Self-service geospatial AI platform built & operated at UMD

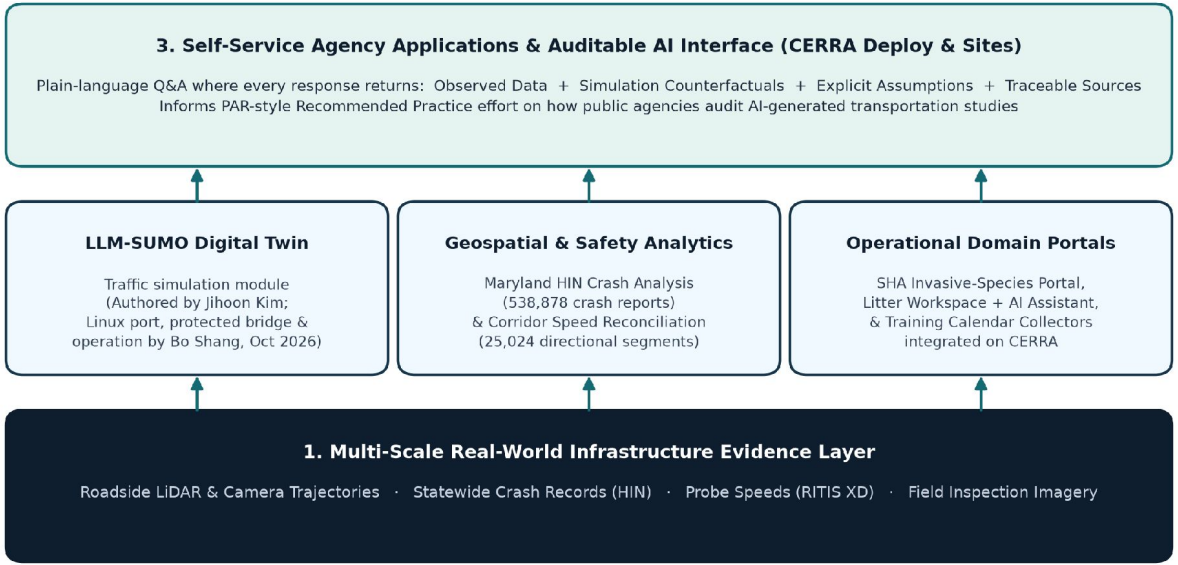
LLM-SUMO (Oct '26)

Plain-language traffic simulation digital twin module

IBM Heron (Oct '26)

First hardware validation of feasibility-preserving VRP

CERRA: Turning Complex Infrastructure Data into Reviewable Evidence



Platform Contribution & Collaborative Attribution: Designed, built, and operated CERRA (Civil, Environmental, Road & Resource Analytics, cerra.cloud) including Deploy & Sites self-service publishing—bringing collaborative M-TRAIL tools and datasets (LLM-SUMO by J. Kim; HIN method by Y. Gong / pilot by K. Chai; SHA portal & litter model by L. Cheng's team) into unified operation.

LLM-SUMO Traffic Digital Twin & Auditable AI Standards

LLM-SUMO Integration on CERRA (Live Oct 2026)

• CERRA itself is the geospatial platform; inside it, LLM-SUMO serves as a working traffic-simulation digital twin.

• Authored by Jihoon Kim; ported to Linux, connected via a protected execution bridge, packaged as a CERRA module, and operated by Bo Shang.

• Converts natural-language prompts into calibrated SUMO network scenarios, executes runs, and summarizes traffic impacts for engineers.

Auditable Decision Support & PAR Standard

• Joins empirical before/after corridor records (e.g., 25,024 directional XD speed segments & HIN crash data) with SUMO counterfactuals.

• Every copilot response must return four elements: Observed Data + Simulation Result + Explicit Assumptions + Sources.

• Observing real failure modes motivated leading a PAR-style Recommended Practice effort on how agencies audit AI-generated traffic studies.

Engineering Boundary

AI-driven simulation explores counterfactuals—it does not replace the traffic engineer. A decision or study an operator cannot audit is a decision a public agency will not deploy.

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Feasibility-Preserving Routing on Quantum Hardware & Quantum-Safe V2X

Feasibility-Preserving VRP on IBM Heron (Oct 2026)

• Penalty-based QUBO encodings often return infeasible routes when solver noise increases.

• Formulated vehicle-routing problems in feasibility-preserving encodings and benchmarked them across classical GA/SA solvers, quantum simulators, and an IBM Heron superconducting processor.

• Honest Empirical Finding: At tested hardware scale, quantum execution shows no advantage over classical baselines; the enduring contribution is the structural feasibility guarantee.

Quantum-Safe V2X Signal Broadcast & Agent Eval

• Evaluates post-quantum cryptographic authentication overhead on roadside SPaT (Signal Phase & Timing) broadcasts so cooperative safety stays trustworthy under strict V2I latency budgets.

• Applies reproducible evaluation (versioned configs, counterbalanced replay, regression guardrails) to tool-using AI agents—documented in open traceability supplements.

Generalizable Lesson Across Physical & Algorithmic Systems

Problem structure—occlusion geometry at intersections, feasibility encodings in routing, and source provenance in AI—rather than raw compute or sensor count is usually the binding constraint in field deployment.

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PART V · NEXT FIVE YEARS

Research Agenda, Teaching & Mentoring

Advancing deployment-grade field robots, open cooperative-perception benchmarks, and auditable autonomy while training the next generation of engineers.

Thrust 1 · Micro

Deployment-grade inspection & active-SLAM field robots

Thrust 2 · Meso/Macro

Network-scale PACO & open InfraLiDAR-Eval suite

Thrust 3 · City/Network

Auditable fleet & infrastructure decision systems

Three Connected Thrusts Across Scales & Target Funding

Thrust 1 · Micro (Proposed)
Deployment-Grade Field Robots

• Combine flight/surface mobility, contact sensing & 3D defect analytics with inspector-in-the-loop reports.
• Proposals in preparation: quadruped work-zone inspection via active SLAM (cone/barrier localization) & rural medical drone delivery (with MDOT).
• Milestones: Multi-structure agency demos & open defect shift benchmark (Yrs 1–3).

Thrust 2 · Meso & Macro (Proposed)
Cooperative Perception & Eval

• Extend PACO from single intersections to sensor networks optimizing multi-RSU placement.
• Release InfraLiDAR-Eval as an open evaluation suite quantifying operating envelopes under beam loss, weather & GPS denial.
• Milestones: Open evaluation suite (Yrs 1–2); municipal field pilot (Yrs 2–4).

Thrust 3 · City & Network (Proposed)
Decisions an Operator Can Audit

• Unify feasibility-preserving fleet/inspection scheduling with calibrated digital twins on CERRA.
• Establish PAR-style auditability metrics so human operators can inspect, override, and defend AI studies.
• Milestones: Autonomous inspection dispatch pilots (Yrs 1–3); transit/logistics routing studies (Yrs 2–5).

Funding Roadmap & Agency Translation

Targets: NSF (CPS, Foundational Research in Robotics, CAREER), U.S. DOT & UTC program, FHWA, PHMSA, and DOE—building directly on co-authored U.S. DOT UTC (2026), INSPIRE-024 (2024), and PHMSA CAAP (2022) federal deliverables.

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Classroom & Laboratory Teaching Grounded in Real Robotic Systems

Multi-Institution Teaching Record

- Vaughn College (2024, Adjunct Faculty & Summer Instructor):
  - MCE 355: Robotics, Mechanics and Control
  - SBC 012 / 014A: Principles of AI & Principles of Research-AI
  - Designed 5-lecture, 5-lab Computer Engineering Summer AI module
- CCNY / CUNY (2023, Adjunct Assistant Professor):
  - ENGR 204: Electric Circuits (mean evaluation: 4.2 / 5.0)
- UC Merced (2016–2017, Lecturer):
  - ME 190 Mechatronics, ME 143 UAS (initial lab development), ME 021

Pedagogy & Proposed Course Offerings

- Pedagogy: Connect analytical models to hardware-in-the-loop failure modes; credentialed with ACUE Effective Teaching Certificate (2021) & FAA Part 107 Remote Pilot Certificate.

- Proposed Courses (Adaptable to Department Needs):
  1. [UG Core] Mechatronics, Controls & Embedded Systems
  2. [UG/Grad] Autonomous Field Robotics & Vision-Based Control
  3. [Graduate] 3D Perception, Cooperative Sensing & Auditable AI for Intelligent Infrastructure

Coursework-to-Field Pipeline

Open-source benchmarks (Simscape/OS4 quadrotor suites, InfraLiDAR-Eval crops, SUMO scenarios) bring real sensor datasets directly into student lab assignments and capstone projects.

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Inclusive Student Mentoring & Verifiable Engineering Impact

Mentoring & Broadening Participation

• Scoped, Publishable Student Sub-Projects:
Sensor bring-up, calibration toolchains, field campaigns, control benchmarks, and reproducible evaluation harnesses.

• Proven Track Record in Diverse Classrooms & Labs:
– Mentored undergraduate, master's, and high-school researchers at minority-serving and public institutions (Vaughn >85% HSI, CCNY, Missouri S&T).
– Coached FIRST Robotics Competition teams (2022) and judged middle/high-school & collegiate VEX Robotics tournaments (2024).

• Forward Lab Culture:
Reproducible code, preserved research evidence, and direct partnership with municipal/state engineers.

Selected Scholarly & Engineering Outputs

• Archival Publications:
– 8 Journal Articles: IEEE OJ-ITS ('26), IEEE T-ASE ('25, IROS '25), JCSHM ('25), CBM ('25), Materials Evaluation ('23), Nonlinear Dynamics ('19).
– 16 Conference Papers: IEEE/CVF CVPRW ('26), MobiSPC ('25 ×2), ICUAS ('16, '17), ICARCV ('18), ASME IDETC ('17, '19).
– Federal Reports: U.S. DOT UTC DOT 91974 ('26), INSPIRE-024 ('24), PHMSA CAAP ('22).

• Patents & Honors:
– U.S. Patent 12,296,994 B2 ('25) & CN Patent 102427464 B.
– BIRDS selected for ASCE 2025 Charles Pankow Award (PI: G. Chen).
– IARC Best System Control & Best Mission Planning Awards.

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Resilient Intelligent Infrastructure Across Scales

Micro (~ m) · Structures

Physics-grounded flight control & dual-mode / climbing robots that inspect bridges and concrete before failure.

Meso & Macro · Roads

Elevated roadside LiDAR resolving the 0.61 onboard occlusion ceiling (PACO) & 61.9-h continuous corridor analytics.

City & Network · Decisions

CERRA geospatial AI, LLM-SUMO simulation, and feasibility-preserving optimization that operators can audit.

Thank You · Questions & Collaboration

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