US DOT National University Transportation Center for Safety

Safety Assurance and Demonstration of Connected Autonomous Vehicles

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Resulting Publications

1. S. Sural and R. Rajkumar, "*TrafficSignReader*: Real-Time Zero-Shot Recognition of Text-Based Traffic Signs", *Intelligent Transportation Systems Conference (ITSC)*, 2025, https://its.papercept.net/conferences/scripts/abstract.pl?ConfID=91&Number=974.

2. Sahu, Nishad, Shounak Sural, Aditya Satish Patil, and Ragunathan (Raj) Rajkumar. "*ObjectTransforms* for Uncertainty Quantification and Reduction in Vision-based Perception for Autonomous Vehicles", *International Conference on Computer Vision (ICCV) Workshop*, Hawaii, USA. IEEE, October 2025, https://www.arxiv.org/pdf/2510.16118.

3. Sahu, Nishad, Gregory T. Su, Shounak Sural, Sean Brennan, and Ragunathan (Raj) Rajkumar. "Towards the Safe Operation of Autonomous Vehicles in Work Zones." In *2025 IEEE Intelligent Vehicles Symposium (IV)*, pp. 2380-2387, 2025, https://dx.doi.org/10.1109/IV64158.2025.11097505.

4. G. T. Su and R. R. Rajkumar, "*Enhanced Safety Messages (ESM)*: A Practical Alternative to V2X Basic Safety Messages," *2025 IEEE 101st Vehicular Technology Conference (VTC2025-Spring)*, 2025, pp. 1-7, https://dx.doi.org/10.1109/vtc2025-spring65109.2025.11174658.

5. G. T. Su and Ragunathan (Raj) Rajkumar, "*MPMP*: A Protocol to Transmit Long Messages for V2X Applications," *2024 IEEE 100th Vehicular Technology Conference (VTC2024-Fall)*, Washington, DC, USA, 2024, pp. 1-7, https://dx.doi.org/10.1109/vtc2024-fall63153.2024.10757449.

6. Sahu, Nishad, Anand Bhat, and Ragunathan (Raj) Rajkumar. "*SafeRoute*: Risk-Minimizing Cooperative Real-Time Route and Behavioral Planning for Autonomous Vehicles." In *2024 IEEE 27th International Conference on Intelligent Transportation Systems (ITSC)*, pp. 2346-2353, https://ieeexplore.ieee.org/document/10919756.

7. Sural, Shounak, Nishad Sahu, and Ragunathan (Raj) Rajkumar. "*ContextualFusion*: Context-based multi-sensor fusion for 3D object detection in adverse operating conditions." In *2024 IEEE intelligent vehicles symposium (IV)*, pp. 1534-1541, https://dx.doi.org/10.48550/arxiv.2404.14780.

8. Sural S, Naren, Rajkumar R, "*ContextVLM*: Zero-Shot and Few-Shot Context Understanding for Autonomous Driving using Vision Language Models", 2024 IEEE 27th International Conference on Intelligent Transportation Systems (ITSC) September 24- 27, 2024. Edmonton, Canada, https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=10920066.

9. Sural, Shounak, Gregory Su, Nishad Sahu, and Ragunathan (Raj) Rajkumar. "*CoSim*: A Co-Simulation Framework for Testing Autonomous Vehicles in Adverse Operating Conditions", In *2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC)*, pp. 2098-2105, https://ieeexplore.ieee.org/document/10422355.

Datasets

1. The code and dataset for “***ContextVLM***” are available at https://github.com/ssuralcmu/ContextVLM.git.
2. The code and dataset for ***TrafficSignReader*** are available at https://github.com/ssuralcmu/TrafficSignReader.git.

Videos

1. AV Operations in Workzones: https://github.com/Nishad-Sahu/Towards_the_safe_operation_of_Autonmous_Vehicles_in_Work_Zones.git

Project Outputs

TrafficSignReader**:** Locating and reading traffic signs is an integral aspect of driving in general and is considered safety-critical for autonomous vehicles (AVs). However, the sheer number of disparate traffic signs and a lack of public datasets pose unique challenges for designing computer vision algorithms to recognize a wide variety of signs. We have proposed ***TrafficSignReader***, a three-stage framework for recognizing text-based traffic signs without the need for category-specific sign data. ***TrafficSignReader*** comprises an object detection stage, an optical character recognition step, and a language-based matching stage for individual sign recognition. Our approach is robust against motion blur, occlusion, glare from streetlights as well as weather conditions. We also create the ***Textual Traffic Sign Dataset***, consisting of about 10,000 textual traffic sign images across 190 classes, covering most of the textual traffic sign categories found in the United States. ***TrafficSignReader*** recognizes textual traffic signs across all these classes with anF1-Score of 95.1%, comparing very favorably with respect to the current state of the art in terms of accuracy, breadth of coverage, generalizability and run-time efficiency. It runs at 10 fps using a lightweight GPU on our CMU AV, reading traffic signs over 50m away and making it feasible for real-world deployment.

ContextVLM: Zero-Shot and Few-Shot Context Understanding for Autonomous Driving using Vision Language Models: In recent years, there has been a notable increase in the development of autonomous vehicle (AV) technologies aimed at improving safety in transportation systems. While AVs have been deployed in the real-world to some extent, a full-scale deployment requires AVs to robustly navigate through challenges like heavy rain, snow, low lighting, construction zones and GPS signal loss in tunnels. To be able to handle these specific challenges, an AV must reliably recognize the physical attributes of the environment in which it operates. Context recognition is the task of accurately identifying environmental attributes for an AV to appropriately deal with them. Specifically, we have defined 24 environmental contexts capturing a variety of weather, lighting, traffic and road conditions that an AV must be aware of. Motivated by the need to recognize environmental contexts, we have created a context recognition dataset called ***DrivingContexts*** with more than 1.6 million context-query pairs relevant for an AV. Since traditional supervised computer vision approaches do not scale well to a variety of contexts, we proposed a framework called **ContextVLM** that uses vision-language models to detect contexts using zero- and few-shot approaches. ***ContextVLM*** is capable of reliably detecting relevant driving contexts with an accuracy of more than 95% on our dataset, while running in real-time on a 4GB Nvidia GeForce GTX 1050 Ti GPU on an AV with a latency of 10.5 ms per query.

ObjectTransforms: Reliable perception is fundamental for safety-critical decision-making in autonomous driving. Yet, vision-based object detector neural-networks remain vulnerable to uncertainty arising from issues such as data bias and distributional shifts. We have introduced ***ObjectTransforms***, a technique for quantifying and reducing uncertainty in vision-based object detection through object-specific transformations at both training and inference times. At training time, ***ObjectTransforms*** perform color-space perturbations on individual objects, improving robustness to lighting and color variations. ***ObjectTransforms*** also uses diffusion models to generate realistic, diverse pedestrian instances. At inference time, object perturbations are applied to detected objects and the variance of detection scores are used to quantify predictive uncertainty in real-time. This uncertainty signal is then used to filter out false positives and also recover false negatives, improving the overall precision–recall curve. Experiments with YOLOv8 on the NuImages 10K dataset demonstrate that our method yields notable accuracy improvements and uncertainty reduction across all object classes during training, while predicting desirably higher uncertainty values for false positives as compared to true positives during inference. Our results highlight the potential of ***ObjectTransforms*** as a lightweight yet effective mechanism for reducing and quantifying uncertainty in vision-based perception during training and inference respectively.

Safe Operations of AVs in Work Zones: Autonomous vehicles (AVs) promise significant advances in transportation safety and efficiency. However, navigating roadway work zones, which can be rather complex and dynamic, remains a significant challenge. We conducted a large study that addresses the challenges, requirements, solutions and practical experiences of AVs driving safely through work zones. We proposed a taxonomy of work zone scenarios and analyzed their structures and attributes. We captured the perception, routing, behavioral and path-planning requirements for AVs to safely navigate these scenarios. We then offered methods to meet these requirements and investigated the impact of range and AV speed on perception confidence levels for work zone detection. We finally evaluate our solutions in a co-simulation environment, on a closed track and on public roadways across more than 20 work zone scenarios specified by the Pennsylvania Department of Transportation (PennDoT). Video demonstrations illustrate the feasibility of safe and reliable navigation of AVs in a wide variety of work zones.

Enhanced Safety Messages (ESM) for V2X Communications: A very important use case of Vehicle-to-Everything (V2X) communications is the enhancement of roadway safety by utilizing the transmission of road information among vehicles. The SAE Basic Safety Message (BSM) is the most common standard used to transmit road event information and their locations based on global latitudinal and longitudinal coordinates of transmitting vehicles. In practice, however, global coordinate estimations are inherently limited by the accuracy of Global Navigation Satellite Systems (GNSS) such as GPS. GNSS signals can also be unavailable in urban canyons and tunnels, be spoofed to force incorrect localization, or be restricted to low accuracy due to the sparsity of available ground-based corrections (such as RTK base stations) in rural and remote areas. We have introduced Enhanced Safety Messages (ESMs), a backward-compatible BSM replacement that adopts the well-established foundations of information redundancy in safety-critical systems to avoid catastrophic failure by providing both absolute and relative coordinate frames to robustly describe vehicle locations. This position information redundancy in two different coordinate systems, one from external sources and another from local sensing, effectively addresses the BSM drawbacks of relying entirely on GNSS signals. Specifically, ESM includes ***LaneContext*** and ***MapContext*** to address two of the most common driving environments of open spaces and urban roadways. Location communication over ESM is enhanced by additionally specifying the connected vehicle's driving lane, its offset from the center of the lane, and its longitudinal position along the road segment. Our experimental evaluation confirms that ESM's inclusion of relative positioning rectifies the core BSM weaknesses in relying only on global GNSS coordinates.

SafeRoute: Autonomous vehicles (AVs) have the potential to mitigate automotive crashes, lower fatalities and optimize energy consumption. Still, the widespread deployment of AVs faces limitations due to practical constraints placed on the Operational Design Domain (ODD) that often excludes challenging scenarios such as work zones and inclement weather conditions. These restrictions pose a considerable obstacle to broader AV deployment. For instance, robotaxis deployed by GM Cruise and Waymo in San Francisco have demonstrated unreliable behavior in work zones. We have introduced a cooperative route-planning and behavioral framework named ***SafeRoute*** designed to mitigate operational safety risks along the routes taken by AVs. ***SafeRoute*** explicitly considers high-risk conditions including work zones, lowvisibility environments and adverse weather conditions to minimize associated risks while avoiding excessively long detours. The weights assigned to various ODD features can be customized as the perception capabilities of AVs improve. Efficient lane-changing mechanisms are designed to handle complex work zones dynamically. ***SafeRoute*** has been integrated into CMU's AV software stack. Extensive testing has been done using an array of work zone scenarios specified by the Pennsylvania Department of Transportation (PennDoT), encompassing simulations, test tracks and real-world public roads (video demos provided). Operating in real-time, ***SafeRoute*** effectively handles a diverse set of challenging scenarios.

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