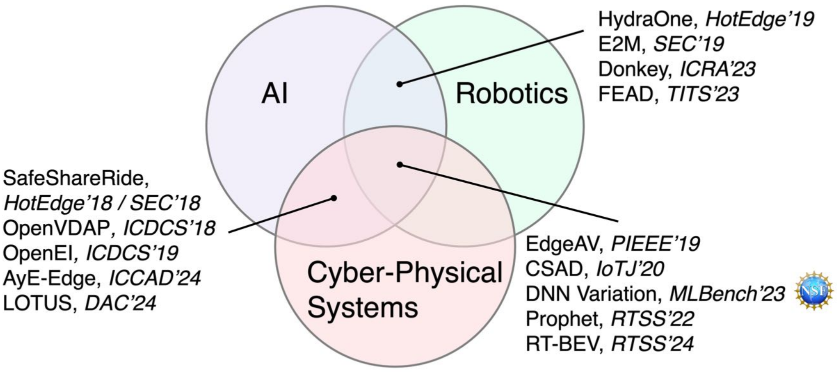
Research Statement

Liangkai Liu, University of Michigan

Research Objective

My research vision is to develop **AI-powered cyber-physical systems** that enhance **autonomy**, **efficiency**, **safety**, and **security** in transportation and robotics. By integrating cyber-physical systems, artificial intelligence, robotics, real-time processing, and edge computing, I aim to create robust and scalable solutions to address the challenges of autonomous driving and intelligent transportation. My goal is to bridge the gap between theory and practice, ensuring that advanced transportation systems are both innovative and reliable in real-world applications.



My work is inherently cross-disciplinary, encompassing cyber-physical systems, artificial intelligence, real-time systems, robotics, intelligent transportation, and edge computing. I have published in top-tier venues like RTSS, RTAS, ICCAD, ICRA, SEC, HotEdge, TITS, IWC, and IoTJ. Notably, I am among the first in the computing systems community to explore the issue of DNN inference time variations in autonomous driving, leading to a **$600,000 NSF Grant** awarded to me as a **Co-Principal Investigator** for research on multi-tenant DNN inference time variations. I have developed testbeds like HydraOne and Donkey, which serve as programmable and energy-efficient platforms for autonomous mobile robots. Additionally, my research on fuel-efficient autonomous trucking has resulted in a 7% reduction in fuel consumption in practical deployments compared to experienced drivers. As of July 31, 2025, my work has received **2,359** citations, with an H-Index of **18** and an i10-Index of **22**.

Prior Research

1. Predictable Perception for Autonomous Vehicles

Ensuring predictability of deep neural networks (DNNs) in AV's perception pipeline presents significant challenges [1]. To address this issue, we conducted a comprehensive profiling of DNN inference time variations [2] and developed novel solutions to achieve predictable perception for AVs. First, `Prophet` mitigates substantial time variations in most DNN models within an AV system through novel early-exit and coordination mechanisms [3]. Second, `PP-DNN` achieves a real-time and predictable pipeline by employing region-of-interest (ROI) processing [4]. Third, `RT-BEV` addresses multi-camera synchronization and detection issues through a co-design of communication and detection, coupled with ROI-based processing [5]. Finally, `AyE-Edge` presents a general solution for power-efficient real-time object detection via the co-design of keyframe selection, model pruning, and CPU-GPU configuration [6].

Inference Time Variations [2]. Understanding the time variations of the DNN inference becomes a fundamental challenge in real-time scheduling for autonomous driving. Therefore, we develop a reconfigurable testbed for DNN inference profiling [7]. On top of that, we analyze the time variation in DNN inference in fine granularity from **six perspectives: data, I/O, model, runtime, hardware, and end-to-end perception system**. Six insights are derived in understanding the time variations for DNN inference [2]. This work contributes to two research papers and one **NSF Grant** for studying *DNN inference time variations for multi-tenant DNNs*.

Inference with Early-Exit [3]. Through a comprehensive empirical study, we found that the inference time variations for a single DNN model are mainly caused by the **DNN's multi-stage/multi-branch structure**, which has a dynamic number of proposals or raw points. In addition, we found that the **uncoordinated contention and cooperation** are the roots of the time variations for multi-tenant DNNs inference. Based on these insights, we proposed the `Prophet` system that addresses the time variations in the AV perception system in two steps [3]. The first step is to predict the time variations based on the intermediate results like proposals and raw points. The second step is coordinating the multi-tenant DNNs to ensure the execution progress is close to each other. The evaluation on the KITTI dataset show effective performance in reducing inference time variations.

Multi-Tenant DNNs Coordination [4]. Existing studies primarily focus on compressing the DNN models to achieve faster perception. In contrast, we present a Predictable Perception system with DNNs (`PP-DNN`) that reduce the amount of image data to be processed while maintaining the same level of accuracy for multi-tenant DNNs by **dynamically selecting 'critical' frames and regions of interest (ROIs)** [4]. `PP-DNN` is based on our key insight that critical frames and ROIs for AVs vary with the AV's surrounding environment, as shown in Figure 1. However, it is challenging to identify and use critical frames and ROIs in multi-tenant DNNs for predictable inference. Given image-frame streams, `PP-DNN` leverages an ROI generator to identify critical frames and ROIs based on the similarities of consecutive frames and traffic scenarios. `PP-DNN` then leverages a FLOPs predictor to predict multiply-accumulate operations (MACs) from the dynamic critical frames and ROIs. The ROI scheduler coordinates the processing of critical frames and ROIs with multiple DNN models. Finally, we design a detection predictor for the perception of non-critical frames. Our evaluations with BDD100K and nuScenes datasets show that `PP-DNN` significantly reduces inference time while maintaing perception accuracy.

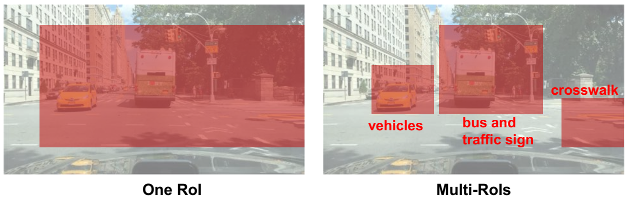


Figure 1: An example of environment-aware dynamic ROIs.

ROI-Aware BEV Perception [5]. For vision-centric Bird's Eye View (BEV) perception, prior work either compresses the dense detection model to reduce computation which can hurt accuracy and assume images are well synchronized, or focuses on worst-case communication delay. To meet this challenge, we propose `RT-BEV`, the first framework designed to **co-optimize message communication and object detection** to improve real-time e2e BEV perception without sacrificing accuracy [5]. The main insight of `RT-BEV` lies in generating **traffic environment- and context-aware Regions of Interest (ROIs)** for AV safety, combined with ROI-aware message communication. `RT-BEV` features an ROI-aware Camera Synchronizer that adaptively determines message groups and allowable delays based on ROIs' coverage. We also develop a ROIs Generator to model context-aware ROIs and a Feature Split & Merge component to handle variable-sized ROIs effectively. Furthermore, a Time Predictor forecasts timelines for processing ROIs, and a Coordinator jointly optimizes latency and accuracy for the entire e2e pipeline. We have implemented `RT-BEV` in a ROS-based BEV perception pipeline and evaluated it with the nuScenes dataset. `RT-BEV` is shown to significantly enhances real-time BEV perception.

Power-Efficient Real-Time Object Detection [6]. Object detection on the edge is in growing demand thanks to its ever-broad application prospects. However, the development of this field is rigorously restricted by the deployment dilemma of simultaneously achieving high accuracy, excellent power efficiency, and meeting strict real-time requirements. To tackle this dilemma, we propose `AyE-Edge`, the first-of-this-kind development tool that explores automated algorithm-device deployment space search to realize accurate yet power-efficient real-time object detection on the edge [6]. Through a **collaborative exploration of keyframe selection, CPU-GPU configuration, and DNN pruning strategy**, `AyE-Edge` excels in extensive real-world experiments conducted on a mobile device. The results consistently demonstrate `AyE-Edge`'s effectiveness, realizing outstanding real-time performance, detection accuracy, and notably, a remarkable 96.7% reduction in power consumption, compared to state-of-the-art (SOTA) competitors.

2. Energy-Efficient Autonomous System

Energy-efficiency has been a fundemental issue for autonomous mobile robots and heavy-duty trucks. Autonomous driving techniques bring potential for saving energy through proper coordination of software stack (perception, planning, and control) and hardware platforms (sensor, computing device, motors, engine management system). Figure 2 shows platforms we built for energy efficinet autonomous system. More specifically, on top of the HydraOne platform [8], E2M coordinates the perception module with computing devices and sensors [9]; Donkey platform extends this to the whole navigation stack with sensor, computing device, and motors [10]; pNav achieves real-time power-efficient navigation for AMRs [11]; FEAD coordinates planning and control with the truck's engine management systems [12].

Energy-Efficient Middleware [9]. By analyzing the breakdown of power dissipation for the execution of computer-vision applications on AMRs and **discover three main root causes of energy inefficiency**: *uncoordinated access to sensor data*, *performance-oriented model inference execution*, and *uncoordinated execution of concurrent jobs*. To address three inefficiencies, we propose E2M, an energy-efficient middleware software stack for autonomous mobile robots [9]. First, E2M regulates the access of different processes to sensor data, e.g., camera frames, so that the amount of data actually captured by concurrently executing jobs can be minimized. Second, based on a predefined per-process performance metric (e.g., safety, accuracy) and desired target, E2M manipulates the process execution period to find the best energy-performance trade off. Third, E2M coordinates the execution of the concurrent processes to maximize the total contiguous sleep time of the computing hardware for maximized energy savings. We have implemented a prototype of E2M on HydraOne [8], a real-world AMR. Our experimental results show that, compared to several baselines, E2M leads to 24% energy savings for the computing platform, which translates into an extra 11.5% of battery time and 14 extra minutes of robot runtime, with a performance degradation lower than 7.9% for safety and 1.84% for accuracy.

Energy-Efficient Path Planning for AMRs [10]. Through empirical studies on real AMRs, we have identified a lack of coordination between computation and control as a major source of energy inefficiency. In this work, we propose **a comprehensive energy prediction model that provides real-time energy consumption** for each component of the AMR [10]. Additionally, we propose three path models to address the obstacle avoidance problem for AMRs. To evaluate the performance of our energy prediction and path models, we have developed a customized AMR called Donkey, which has the capability for fine-grained (millisecond-level) end-to-end power profiling. Our energy prediction model demonstrated an accuracy of over 90% in our evaluations. Finally, we applied our energy prediction model to obstacle avoidance and guided energy-efficient path selection, resulting in up to a 44.8% reduction in energy consumption compared to the baseline.

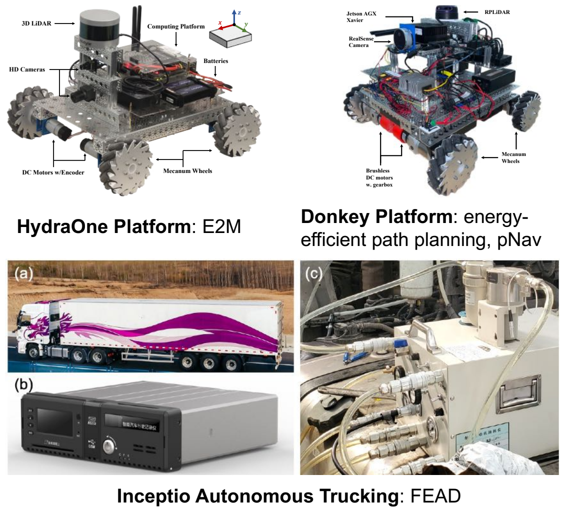


Figure 2: Testbeds for Energy Efficient Autonomous System.

Power-Efficient Navigation of AMRs [11]. `pNav` is a novel power-management system designed to enhance the power/energy-efficiency of Autonomous Mobile Robots (AMRs) by **jointly optimizing their physical/mechanical and cyber subsystems** [11]. From power profiling on robots, we identified three types of inefficiency in current AMRs designs that combine cyber (C) and physical (P) subsystems: (1) unawareness of power-breakdown variations, (2) uncoordinated C and P subsystems, and (3) neglect of navigation localities. To achieve proper coordination of C and P subsystems for power-efficiency, `pNav` employs a multi-faceted approach. First, `pNav` integrates millisecond-level power consumption prediction for both C and P subsystems. Second, `pNav` includes novel real-time modeling and monitoring of spatial and temporal navigation localities for AMRs. Third, `pNav` supports dynamic coordination of AMR software (navigation, detection) and hardware (motors, DVFS driver) configurations. `pNav` is prototyped using the Robot Operating System (ROS) Navigation Stack, 2D LiDAR, and camera. Our in-depth evaluation with Donkey and Gazebo environments demonstrates a >96% accuracy in predicting power consumption and a 38.1% reduction in power consumption without compromising navigation accuracy and safety.

Fuel Efficient Autonomous Trucking [12]. Fuel cost contributes significantly to the high operation cost of heavy-duty trucks. Developing fuel rate prediction models is the cornerstone of fuel consumption optimization approaches for heavy-duty trucks. However, limited by accurate features directly related to the truck's fuel consumption, state-of-the-art models show poor performance and are rarely deployed in practice. In this work, we **use the truck's engine management system (EMS) and Instant Fuel Meter (IFM)** to collect a three-month dataset during the period of December 2019 to June 2020 [12]. Seven prediction models, including linear regression, polynomial regression, MLP, CNN, LSTM, CNN-LSTM, and AutoML, are investigated and evaluated to predict real-time fuel rate. The evaluation results show that the EMS and IFM dataset help to improve the coefficient of determination of traditional linear/polynomial models from 0.87 to 0.96, while learning-based approach AutoML improves the coefficient of determination to attain 0.99. Besides, the actual deployment of fuel rate prediction and path planning show up to 7% fuel saving on real Inceptio trucks [13].

3. Vehicular Edge Computing Framework

Connected and Autonomous Vehicles (CAVs) is becoming more and more popular for automobile academic and industry community. I have worked on building a practical framework for CAVs atop the co-design of communication, computation, and control [14]. We also prototype and profile real autonomous driving vehicles as well as road-side unit, including the Hydra AV Testbed, and the Equinox platform [8, 15]. On top of Equinox and Hydra, we profile the communciation performance for V2X communciations [16]. Futhermore, I proposed SafeShareRide, which is an edge computing-enabled system for protecting both driver and passenger's safety [17, 18].

Communication, computation, and control Co-design [14]. To improve the end-to-end performance, we envision that future CAVs require co-design of communication, computation, and control [14]. This article presents our vision of the end-to-end design principle for CAVs, called 4C, which provides a unified communication, computation, and control co-design framework. With **programmable communications, fine-grained heterogeneous computation, and efficient vehicle controls** in 4C, CAVs can handle critical scenarios and achieve energy-efficient autonomous driving.

Vehicular Communication Comparison [16]. Communication mechanisms play an important role in CAVs applications and services. However, lack of detailed comparison of different communication mechanisms is the main obstacle for the deployment of CAVs applications and services. In this work, we **built an end-to-end prototype by integration of Equinox** [15] and HydraOne [8] which supports WiFi, LTE, and DSRC based communications and evaluate the performance in latency, power dissipation, and system utilization [16].

SafeShareRide [17]. Ridesharing services, such as Uber and Didi, are enjoying great popularity; however, a big challenge remains in guaranteeing the safety of passenger and driver. We propose an edge-based attack detection in ridesharing services, namely `SafeShareRide`, which can **detect dangerous events happening in the vehicle in near real-time** [18, 17]. `SafeShareRide` is implemented on both drivers' and passengers' smartphones. `SafeShareRide` is the world's first framework which can support real-time attack detection in ridesharing services.

Future Directions

Looking ahead, my research will address critical challenges in **real-time, safe, and secure cyber-physical systems and intelligent transportation**. By advancing methodologies in these domains, I aim to enhance the robustness, reliability, and performance of such systems in complex and dynamic environments.

End-to-End Framework for CAVs. I plan to develop comprehensive **end-to-end** testing methodologies for connected and autonomous vehicles (CAVs) that cover every aspect of their operation—from perception to control. This holistic approach is essential for ensuring robustness and safety across a wide range of real-world scenarios. A key component of this work will be the creation of **universal metrics applicable to diverse security challenges**, enabling accurate assessment of different strategies' strengths and limitations. These metrics will evaluate multiple facets of the AV pipeline, helping to identify where attacks and defenses are most effective and to quantify their impact on functional safety. By providing deeper insights into **systemic threats and vulnerabilities**, this research will contribute to the development of more secure and reliable autonomous vehicle systems.

Cross-Layer Security Analysis for CAVs. To improve the safety and trustworthiness of CAVs, I plan to investigate **vulnerabilities that span the entire system stack—**from hardware and sensing to perception, planning, and control. Rather than treating each layer in isolation, this research will adopt a **holistic, cross-layer approach** to understand how failures or attacks in one module can propagate and compromise overall system integrity. I will study diverse attack vectors—such as sensor spoofing, adversarial ML inputs, and control hijacking—and examine how they interact across component boundaries. By integrating insights from hardware faults, software vulnerabilities, and AI model behavior, I aim to develop **coordinated defense strategies** that address threats at multiple abstraction levels. This work will help establish a unified framework for assessing and enhancing the **security posture of general CAV systems**, ultimately contributing to the development of more resilient and trustworthy autonomous platforms.

Predictable Offroad Autonomous Driving. I also aim to tackle the unique challenges of offroad autonomous driving, where **unpredictable conditions**—such as fast-moving objects, irregular terrain, and sudden elevation changes—impose stringent, dynamic timing and accuracy requirements on ML-based perception pipelines. To address these challenges, I envision a **collaborative sensing architecture** that employs a heterogeneous sensor suite, including drones and advanced sensing technologies, to enhance situational awareness. By integrating diverse sensor inputs and developing robust perception and control algorithms capable of real-time adaptation, my goal is to design autonomous vehicles that can reliably and safely navigate offroad environments. This research will extend the reach of AV technologies to mission-critical domains such as agriculture, disaster response, and exploration.

Efficient Foundation Models in Cyber-Physical Systems. Foundation models in vision, language, and audio are increasingly being adopted in cyber-physical systems (CPS) for applications including autonomous driving, smart healthcare, and precision agriculture. These models empower CPS to perceive and reason about complex environments, enhancing decision-making and autonomy. However, integrating such computationally intensive models into resource-constrained platforms poses significant challenges—particularly with respect to energy efficiency and real-time performance. I advocate a **co-design approach** that jointly optimizes algorithms, system architectures, and hardware accelerators to enable efficient inference and training. This work will facilitate the practical deployment of foundation models in real-world CPS applications while maintaining high performance and low energy consumption.

Potential Funding Sources

To support this research agenda, I plan to collaborate with leading institutions and industry partners in autonomous systems, edge computing, and intelligent transportation. I will pursue funding from a diverse range of sources beyond the National Science Foundation (**NSF**), including the Department of Transportation (**DOT**) for CAV safety and predictability, the Department of Energy (**DOE**) for energy-efficient computing, and the Defense Advanced Research Projects Agency (**DARPA**) for cutting-edge autonomous and edge systems. I will also seek support through industry-sponsored programs from companies such as **NVIDIA**, **Autoware**, **Toyota**, **Ford**, **GM**, and **Waymo**, and explore international funding through European Union Horizon programs. Additionally, I will leverage existing NSF projects and collaborate with national labs like Argonne for large-scale validation. Securing diverse funding streams will ensure the long-term sustainability of my research and foster interdisciplinary innovation.

References

[1] Liangkai Liu, Sidi Lu, Ren Zhong, Baofu Wu, Yongtao Yao, Qingyang Zhang, and Weisong Shi. Computing systems for autonomous driving: State of the art and challenges. IEEE Internet of Things Journal (IoTJ), 8(8):6469–6486, 2020.

[2] Liangkai Liu, Yanzhi Wang, and Weisong Shi. Understanding time variations of DNN inference in autonomous driving. MLSys Workshop on Benchmarking Machine Learning Workloads on Emerging Hardware, 2023.

[3] Liangkai Liu, Zheng Dong, Yanzhi Wang, and Weisong Shi. Prophet: Realizing a predictable real-time perception pipeline for autonomous vehicles. In IEEE Real-Time Systems Symposium (RTSS), pages 305–317. IEEE, 2022.

[4] Liangkai Liu, Kang G. Shin, Chengmo Yang, and Weisong Shi. Predictable DNN inference for autonomous vehicles. In under review.

[5] Liangkai Liu, Jinkyu Lee, and Kang G. Shin. RT-BEV: Enhancing real-time BEV perception for autonomous vehicles. In 45th IEEE Real-Time Systems Symposium (RTSS), 2024.

[6] Liangkai Liu*, Chao Wu*, Yifan Gong*, Mengquan Li, Yushu Wu, Xuan Shen, Zhimin Li, Geng Yuan, Weisong Shi, and Yanzhi Wang. AyE-Edge: Automated deployment space search empowering accuracy yet efficient real-time object detection on the edge. In International Conference on Computer-Aided Design (ICCAD), 2024.

[7] Liangkai Liu, Yanzhi Wang, and Weisong Shi. CPT: A configurable predictability testbed for DNN inference in AVs. Tsinghua Science and Technology, 30(1):87–99, 2024.

[8] Yifan Wang, Liangkai Liu, Xingzhou Zhang, and Weisong Shi. HydraOne: An indoor experimental research and education platform for CAVs. In 2nd USENIX Workshop on Hot Topics in Edge Computing (HotEdge 19), 2019.

[9] Liangkai Liu, Jiamin Chen, Marco Brocanelli, and Weisong Shi. E2M: An energy-efficient middleware for computer vision applications on autonomous mobile robots. In Proceedings of the 4th ACM/IEEE Symposium on Edge Computing (SEC), pages 59–73, 2019.

[10] Liangkai Liu, Ren Zhong, Aaron Willcock, Nathan Fisher, and Weisong Shi. An open approach to energy-efficient autonomous mobile robots. In IEEE International Conference on Robotics and Automation (ICRA), 2023.

[11] Liangkai Liu, Weisong Shi, and Kang G. Shin. Power-efficient navigation of autonomous mobile robots. In under review.

[12] Liangkai Liu, Wei Li, Dawei Wang, Yi Wu, Ruigang Yang, and Weisong Shi. Fuel rate prediction for heavy-duty trucks. IEEE Transactions on Intelligent Transportation Systems (TITS), 24(8):8222–8235, 2023.

[13] Inceptio Completes Delivery of 300 Autonomous Heavy-Duty Trucks to YTO Express. https://en.inceptio.ai/news/99012.html.

[14] Liangkai Liu, Shaoshan Liu, and Weisong Shi. 4C: A computation, communication, and control co-design framework for CAVs. IEEE Wireless Communications, 28(4):42–48, 2021.

[15] Liangkai Liu, Yongtao Yao, Ruijun Wang, Baofu Wu, and Weisong Shi. Equinox: A road-side edge computing experimental platform for CAVs. In International Conference on Connected and Autonomous Driving (MetroCAD), pages 41–42. IEEE, 2020.

[16] Liangkai Liu, Baofu Wu, and Weisong Shi. A comparison of communication mechanisms in vehicular edge computing. In 3rd USENIX Workshop on Hot Topics in Edge Computing (HotEdge 20), 2020.

[17] Liangkai Liu, Xingzhou Zhang, Mu Qiao, and Weisong Shi. Safeshareride: Edge-based attack detection in ridesharing services. In IEEE/ACM Symposium on Edge Computing (SEC), pages 17–29. IEEE, 2018.

[18] Liangkai Liu, Xingzhou Zhang, Mu Qiao, and Weisong Shi. SafeShareRide: Edge-based attack detection in ridesharing services. In USENIX Workshop on Hot Topics in Edge Computing (HotEdge 18), Boston, MA, 2018. USENIX Association.