PROJECT DESCRIPTION

Research Goals

The PI’s primary research goal is to **explore and find fundamental principles of brain-inspired machine intelligent systems**, including highly automated mobile robots and autonomous vehicles. To achieve this goal, the PI has taken two different approaches: bottom-up data-driven and top-down theory-driven approaches. The fundamental principles of bio-inspired machine intelligence reside around the intersection of these two opposite approaches. The PI has investigated the neuronal and vascular structures of the brain to understand its function. A grant (Award # 1337983) was awarded to the PI from the National Science Foundation (NSF) through the Major Research Instrument (MRI) *Development* program from 2013 to 2016. With the grant, the PI was able to build a high-throughput and high-resolution 3D tissue scanner for large-scale automated histology. The tissue scanner has a 3D virtual microscope that allows us to investigate the neuronal structures of a whole mouse brain in a high resolution. This bottom-up and data-driven approach can provide fundamental insights into us regarding neural circuitry between sensorimotor and cognitive processes. The approach from the other side is top-down and theory-driven. True machine intelligence can be investigated through studies of self-awareness, embodiment, consciousness, and cognitive modeling. The PI has studied the internal dynamics of neural systems to investigate the self-awareness of neural network based-machines and neural signal delay compensation models. These two complementary approaches meet in the middle where true machine intelligence can be implemented as a form of mechanical systems such as highly automated mobile robots and autonomous vehicles. The PI’s research is to bridge the gap between the data-driven and theory-driven approaches.

The proposed project is to provide an essential tool by which the PI will be able to investigate the top-down and theory-driven research on brain-inspired intelligent robotics.

The PI’s role in research on intelligent systems is critical in his institution. The PI recently received an MRI award (Award #2214830) from NSF to acquire an autonomous plug-in hybrid vehicle platform that will be a core asset for educating students and conducting research on various topics of highly automated or autonomous vehicles. To continue high-quality research, students with proper skills are essential. The proposed project will be utilized after its completion to educate students through new or existing courses and to conduct research with students. The proposed project will provide the institution with better opportunities for education and research as an additional resource for students' hands-on experience with highly automated intelligent robotic agents.

Research Project

This project aims to research a novel and innovative design of a Mesoscale Robotic Open-source Vehicle platform for Education and Research in Autonomy or M-ROVER-A. The proposed platform, M-ROVER-A, will be implemented on a mid-size electric four-wheel ride-on car. A design of Drive-By-Wire (DBW) systems will also be explored, and a sensor suite will be proposed for the platform. To validate the system's capabilities to be used as a full-featured research platform, the project will also design full-stack software for developing and testing deep learning and AI-based perception, planning, and control algorithms. M-ROVER-A is a four-wheel (Ackermann steering [1]) mesoscale electric ride-on car that can be controlled programmatically through a DBW system, which is also to be designed and developed by the proposed project. Through the aforementioned functions, M-ROVER-A will be able to emulate a full-scale education and research platform for highly automated or autonomous vehicles to maintain affordability. A detailed plan of the adaptation of M-ROVER-A to a full-scale vehicle will be provided through the proposed activities.

The new industry of highly automated mobile robots, including autonomous vehicles, is in high demand for skilled engineers. Engineers for the industry require interdisciplinary knowledge and skillsets, including basic programming skills, electric circuitry, robotic kinematics, artificial intelligence, motion planning, machine learning, and data science. To answer the high demand for skilled researchers and engineers in highly automated mobile robots and autonomous vehicles, academia must be ready to cultivate students for the areas. The proposed project is to design and implement a hardware and software platform to provide researchers and students with resources for their hands-on experience. To train students with such diverse skills, it is crucial to have proper instruments for hands-on experiences of them. The best option could be using a group of full-scale vehicles powered by DBW systems with sensor suites. Yet, the cost of such an instrument is prohibitive in many cases, putting aside maintenance costs. Vehicular instruments are safety-critical, implicating any modification of the system and experiments with the vehicle can raise safety issues. Using a full-scale vehicle in the early stages for researchers and students might not be ideal due to the reason. Another choice is to use Hardware-In-the-Loop (HIL) to reduce the potential risks, but HIL needs an actual vehicle which is a big portion of the cost of an instrument. Therefore, HIL also implies a high cost to purchase and maintain the instrument. One of the other popular choices is to use small-scale vehicular models. The MIR RACECAR [2], F1TENTH [3], MuSHR [4], Go-CHART [5], Duckiebots of Duckietown [6], Donkey Car [7], Amazon DeepRacer [8], NVIDIA Jetson [9] Nano-based two-wheel differential driving robots, JetBots [10] are part of the efforts. Fig. 1 lists the aforementioned small-scale cars.

Fig 1: Existing Small-Scale Car Robots.
They are small-scale, and onboard computers are Jetson family or Raspberry Pi.

The MIT RACECAR, F1TENTH, and MuSHR use a 1/10th scale electric Remote Control (RC) car (Ackermann steering [1]) powered by an NVIDIA Jetson series embedded computer. NVIDIA Jetson is supported by JetPack [11], enabling deep learning and AI-based computer vision through NVIDIA CUDA, cuDNN, and TensorRT. The NVIDIA Jetson family shows reasonable performance considering its small form factor, but it is not enough to emulate a full-scale vehicular platform. Other groups, such as Duckiebots, Donkey Car, DeepRacer, and JetBots, use even smaller platforms (1/32nd, 1/24th, 1/18th, or 1/16th) powered by either NVIDIA Jetson or Raspberry PI series. Most use two-wheel differential driving, which is not proper for learning four-wheel vehicle kinematics.

A major limitation of the current approaches, however, is in the following two dimensions: (1) **The lack of reproducibility** owing to heavy craftsmanship requirements due to extensive modifications of the vehicular platform (removal and replacement of motors, installation of a new ESC (Electronic Speed Controller), custom Printed Circuit Boards (PCBs), etc. (2) **The restricted *onboard* processing capabilities** due to the platform size. To address the major limitations, this project brings forward an innovative idea of building a **mesoscale** vehicle (about 1/4th) **without extensive modification** and providing **full-stack software for AI-based perception, planning, and control**.

The main goals of the project are to following three: (1) **Enhancement of its reproducibility** so that anyone who is interested in the proposed work can easily build and test and then use it for their education and research. (2) **Provision of full-stack software for AI-based algorithms** for safety-critical systems such as highly automated driving so that algorithms can be tested and validated with the scaled platform before deploying to the full scale. (3) **Better affordability** so that a fleet of the platform can be easily built for a hands-on experience for students in education and research on connected vehicles. By adopting a modular approach, M-ROVER-A allows us to plug in a laptop or desktop as the vehicle's main computing resource. A user can use one's laptop for algorithm development, and the computer can also be used for the vehicle as the main computing resource. By achieving the aforementioned main goals, M-ROVER-A will be able to significantly facilitate research and education activities in the areas of highly automated or autonomous driving and intelligent mobile robotic systems.

The overall system diagram is illustrated in Fig. 2. The onboard controller will be an open-source controller for unmanned aerial, underwater, and ground vehicles. Low-dimensional sensors such as an Inertial Measurement Unit (IMU) and Global Positioning System (GPS) will be directly connected to the onboard controller. A dual-channel motor controller will take care of the steering wheel and driving motors. Electric power will be harnessed from the vehicle's battery to the motor controller to drive motors. Executions of AI-related algorithms will be done on a fully-featured GPU-accelerated computer, which also takes care of high-dimensional sensors such as vision and LiDAR (Light Detection And Ranging) sensors. The design exploration of each component will be discussed in later sections. The PI has experience in a prototype of a similar approach [12], but the vehicle needed a custom-designed control module which made it less reproducible and significant modifications of the vehicle platform, including 3D printed parts to attach rotary encoders.

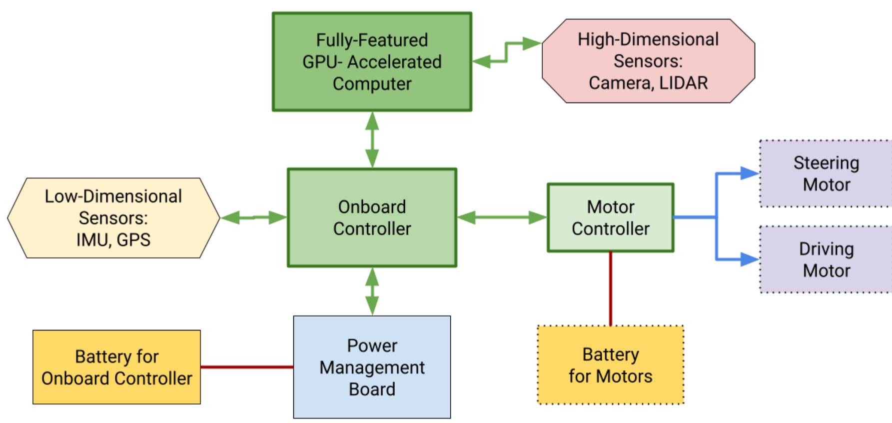


Fig. 2: Hardware System Architecture Diagram

Vehicle Platform

Minimum Requirements: M-ROVER-A will use approximately 1/4th scale electric ride-on vehicle with Ackermann steering as the body of the vehicle. The choice of vehicular platform is based on several factors. First of all, unlike small-scale vehicles based on RC cars, the size of the vehicle must be large enough to carry a full-featured GPU computer with a sensor suite. Second, the battery power of the vehicle must at least be more than two to three hours of driving. Third, the maximum load is more than 20 kg considering a regular-size desktop computer's weight (about 15 kg). One of the potential choices of the vehicle is the EFI V Twin High-Speed Ride-On Car (See Fig. 3). The M-ROVER-A design will consider any similar vehicles as an alternative to this vehicle.

Fig. 3: Dimension of the Proposed Vehicle

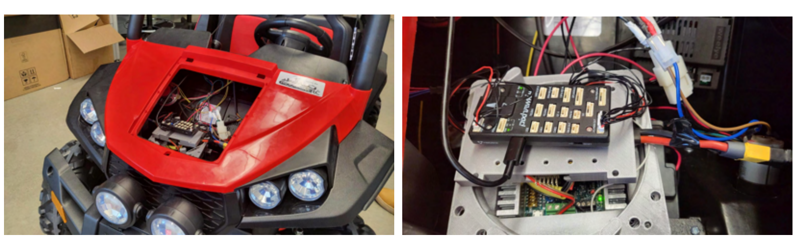
The detailed specifications of the vehicle are as follows and are met with the minimum requirements.

- Dimensions: 130 cm x 94 cm x 83 cm
- Seat width: 58 cm
- Weight: 38.00 kg.
- Max load: up to 35 kg, tested load capacity: 55 kg
- Speed: 3 ~ 7 km/h.
- Drive: 4 x Motor 12V 45W
- Battery: 2 x 12 V
- Charging time: 5-8 hours
- The driving time: 2 to 3 hours

Vehicle Modification: To enhance the reproducibility of the proposed project, M-ROVER-A proposes not to change the vehicle or minimize any modifications. Any electrical and mechanical parts to harness the vehicle's power will not be modified. The proposed DBW system is a module that can be plug-in and out to the vehicle. With complete disablement of the DBW, the vehicle operates as its original function. This approach will significantly improve the reproducibility of the proposed vehicle.

Power and Wiring

Taking the high reproducibility of the proposed design into consideration, the PI proposes to use the batteries of the electric vehicle as a power source for the motor control driver. The original control box is intact (See Figs. 4 and 5). M-ROVER-A suggests using the original control box to send steering signals and motor signals.



(a) (b)

Fig. 4: Power and Wiring. Without re-wiring, the proposed DBW module can reside under the vehicle's hood. (a) The hood is open. Everything will be under the hood. (b) The onboard controller is in action.

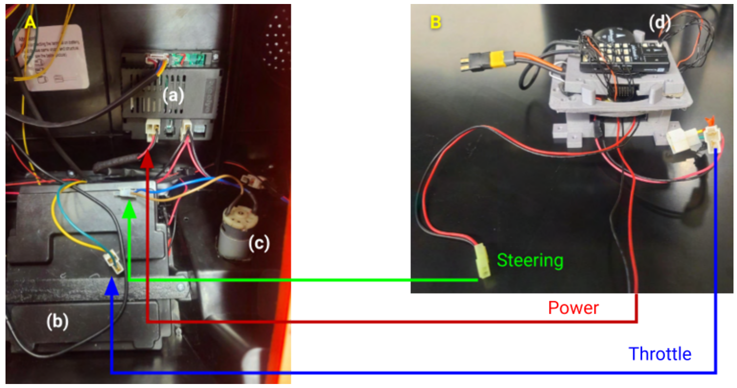


Fig. 5: Wiring Diagram.
A: Under the hood. (a) control box, (b) battery, and (c) steering motor. B: Onboard controller. (d) Pixhawk 4.

Drive-By-Wire (DBW) System

Onboard Controller: M-ROVER-A proposes to use Pixhawk [13]. There are many variations of Pixhawks. As of writing this proposal, Pixhawk 4 [14] with FMUv5 is a reliable choice in terms of the community support by PX4 Autopilot [15], which is a powerful open-source autopilot flight stack, originally designed for drones but now supports underwater and ground vehicles as well. Pixhawk 4 powered by STM32F765 (32-bit ARM Cortex-M7 processor) has onboard sensors such as two accelerometers/gyros and a magnetometer. For interfaces, Pixhawk 4 has ports for several PWM inputs/outputs, three I2Cs, four SPIs, two CAN buses, and analog inputs. Pixhawk was originally developed for drones, so the weight and dimensions of the controller are virtually ignorable for ground vehicles (weight: 15.8 g and dimensions: 44x84x12 mm).

Pixhawks are supported by the PX4 Autopilot ecosystem, which is an open-source *flight* control software for drones and other unmanned vehicles [16] and is supported by very active worldwide communities.

The choice of an onboard controller is critical to maintaining high reproducibility. The communication between a GPU computer and the onboard controller (Pixhawk 4) can be done through MAVROS [17], which is MAVLink [18] extendable node. This means that no additional hardwires are necessary between the GPU computer and the vehicle's original control system to control motors. The algorithms running on the GPU computer talk only to Pixhawk 4 through the MAVROS package, which enables MAVLink communication between them. This design choice is critical to make the proposed system be free from the necessity of custom PCBs, additional hardware, and electric wires.

Motor Controller: To control a steering motor and driving motors, either a dual-channel motor or two motor controllers are required. To maintain the design simplicity, M-ROVER-A suggests a single dual-channel motor driver. The PI has tested a Sabertooth dual 32A motor driver [19] and validated the 32 Ampere is enough to drive a steering motor and driving motors. The dimensions of the motor driver are 70x90x25 mm.

Full-Stack Software

The PI has been developing an open-source project, OSCAR (Open-Source robotic Car Architecture for Research and education) [20] that is based on Robotic Operating System (ROS) [20] and PX4 Autopilot [15]. Fig. 6 illustrates the overall diagram of OSCAR.

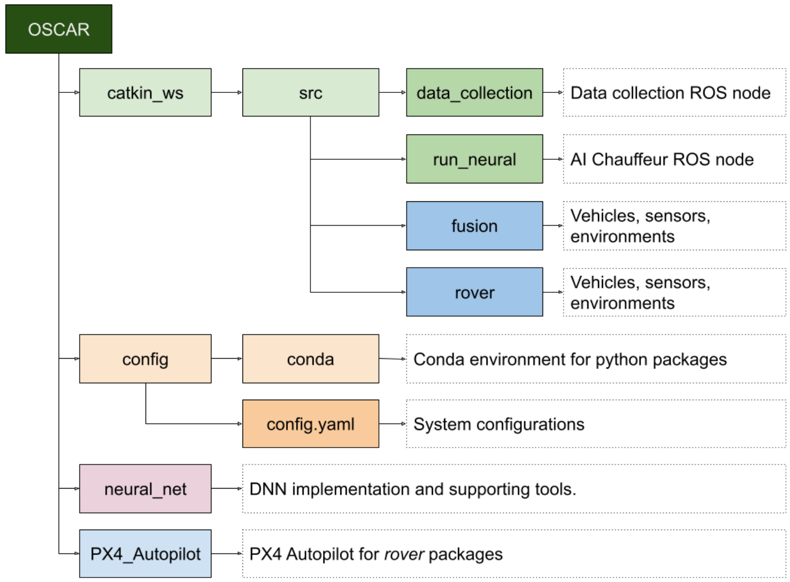


Fig. 6: OSCAR Software Diagram

The modular design of the OSCAR supports multiple vehicles. As of writing this proposal, one full-scale *simulated* Ford Fusion and one full-scale *simulated* Polaris Ranger are supported. With the support of the proposed project, OSCAR will be extended to support physical platforms, including M-ROVER-A and a full-scale vehicle. OSCAR has a framework to support algorithm development for Deep Neural Network (DNN) based perception, planning, and control. OSCAR provides methods for preparing DNN training, including data acquisition and data post-processing. The `neural_net` package supports actual training, validation, and testing. Fig. 7 shows a screenshot of the OSCAR.

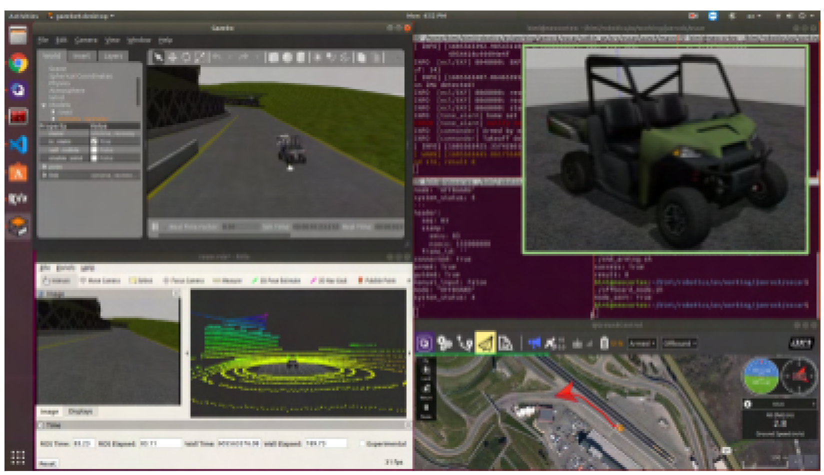


Fig. 7: Screenshot of OSCAR. A *simulated* Polaris Ranger is inset.

The communication between ROS nodes in a GPU computer and the onboard controller (Pixhawk 4) will be through MAVROS. As described in the DBW section, this design choice is critical to make the proposed system keep higher reproducibility. The basic approach of OSCAR has been validated through research activities in [12, 21].

Sensor Suite

Low-dimensional sensors such as accelerometers/gyros and a magnetometer are embedded in the onboard controller. A GPS sensor can also be attached to the controller. Only high-dimensional sensors that are needed to connect to the main GPU computer will be discussed. A vision sensor is required. Intel RealSense Depth Camera [22] can be an option. The depth function of the camera can be an alternative to expensive LiDAR sensors, at least indoor environments. Three cameras are recommended. One is facing the front, and the others are facing the left and right. This three-camera setting inspired by [23] is to develop vision-based end-to-end lane-keeping capability. Additionally, radar and ultrasonic sensors can be attached to the vehicle, and their interfaces will be managed by the main GPU computer. As long as the high-dimensional sensors have their ROS drivers, they can be used for the proposed platform.

Assessment of Success

To assess the success of the proposed work, the PI suggests the following tasks.

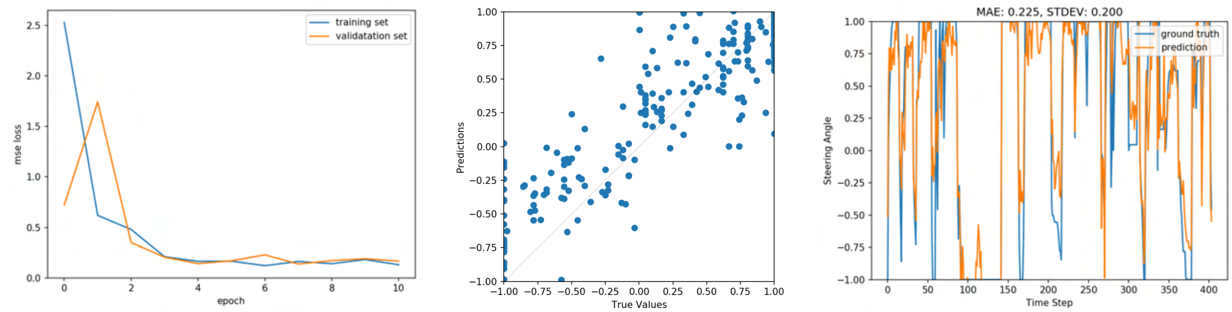
Using the Proposed Design in Real-World Research: As an example to validate the capability of the proposed design, end-to-end behavior cloning [23] can be used. To show the potential of the proposed work, the PI conducted a toy-scale end-to-end behavior cloning task with a quick prototype. With the OSCAR's data collection module, about 25,000 images with labeled steering angles were collected. Fig. 8 shows snapshots of the data collection process. A user drove the vehicle with a remote controller while the data collection module is activated.

Fig. 8: Data Collection.
A user can control the vehicle with a remote controller. The data collection module saves incoming images to the front camera with information about the vehicle, including steering angles, position, velocity, acceleration, etc.

In this prototyping test, a neural network architecture was borrowed from the PI's previous work [21]. The input images were cropped with a region of interest and rescaled into 160x160. Five successive convolution layers were stacked, and the filter sizes were 5x5 (the first three layers) and 3x3 (the next two layers). After flattening the last convolutional layer, dense (fully connected) layers were stacked with 1,000, 100, 50, 10, and finally one. The final output node is a steering angle prediction.

Fig. 9 depicts the training results. The neural network training with the samples was done for 10 epochs with a nice saturation of MSE losses (Fig. 9 (a)). Using the label vs. predicted value in Fig. 9 (b), it is roughly said that the training was somewhat successful. Some of the predicted values were not accurate for the maximum steering angle to the right (-1 is for the right and 1 is for the left). The result in Fig. 9 (c) looks promising. With some exceptions, the prediction values follow the ground truth in most time steps. Fig. 10 shows qualitative results where the gray steering wheel is a ground truth value and the green is a prediction.

In addition to this example, other advanced research can be conducted to validate the success of the project. Some potential research activities are as follows. (i) Research on various cyber attacks can be tested without worrying about safety. (ii) Lane following assistant can be validated in a scaled environment. (iii) Vision-based multiple object tracking can be safely tested and validated with the proposed project.



(a) (b) (c)

Fig. 9: Training Results.
(a) MSE loss (b) Prediction vs. Label (c) Plot for prediction and label steering angle values

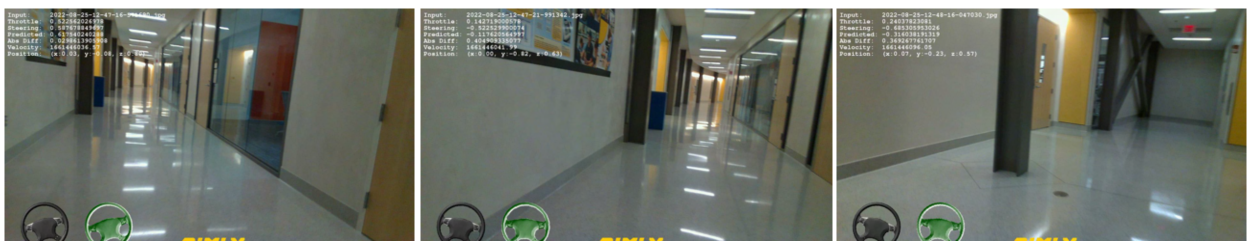


Fig. 10: Qualitative Results of the Steering Angle Predictions.

The PI will exploit existing robotics, automotive, and computer vision courses to encourage the adoption of the proposed platform in their lab sessions. Candidate courses are ECE-4641 Mobile Robotics, ECE-588 Robot Vision, ECE-560 Modern Control Theory, ECE-587 Selected Topics in Computer Vision, ECE-644 Advanced Robotics, ECE-531 Intelligent Vehicle systems, and ECE-533 Active Automotive Saftey Systems. If at least more than three courses show their interest, and two of them actually adopt the platform, the project will be considered a success.

Reproducibility: The PI will compose build instructions such as [24–26], organize a group of ten students, and let them build their own M-ROVER-A just using the build instructions. Then the project team will make checkpoints to find any improvements necessary to even more enhance its reproducibility. If more than 70% of students successfully built the proposed platform without additional help or guidance, the project will be considered a success.

Affordability: The PI will carefully choose components to maintain the affordability of the proposed work. If the total material cost of the core part except for additional depth sensors and a GPU computer is less than $500, the project will be considered a success.

Project Timeline

Project timeline (Sep 1, 2023 - Aug 31, 2024)						
Work	Year 1			Year 2		
	F	W	S	F	W	S
Comparative study of small-scale and full-scale vehicular platform	H	H	L			
Design exploration of mesoscale electric vehicle	-	H	H	L		

Comparative study of multiple design ideas	-	-	H	H	M	L
Start building the platform	-	-	-	H	H	H
Conduct sample research tasks	-	-	-	-	H	H
Build a website to disseminate the design	-	-	-	-	M	H
Dissemination	-	-	-	-	L	H
F (Fall), W (Winter), S (Summer) **Effort Level**: L (Low), M (Medium), H (High)						

Broader Impacts

M-ROVER-A will leverage significant improvements in the research and training infrastructure for highly automated and autonomous mobile robots.

Impact on Research Infrastructure

The demands for research on autonomous mobile robots, including highly automated or autonomous vehicles, are high. Yet, due to the inhibitive cost of purchasing and maintaining such instruments, many schools with no large research funds cannot imagine conducting high-quality research in the rapidly growing areas. The proposed research platform will substantially improve the research infrastructure by providing researchers with crucial equipment to conduct fundamental research in advanced mobility areas. The research areas to be enabled by the proposed project are as follows: (i) Bio-inspired machine intelligence and embodied cognitive vehicles that require a fleet of mobile robots (or vehicles) to test cooperative decision-making. (ii) Vehicular sensor security research that needs realistic but no risk of real harm to the vehicle invoking critical safety issues. (iii) Sensor fusion for the improved perception that requires multiple sensors and control systems.

Impact on Training Infrastructure

The University of Michigan-Dearborn (UM-D), located in Dearborn, which is the Metro Detroit area, surrounded by underrepresented minority communities, has committed to offering high-quality research training and education. Many universities in a similar situation with UM-D can be impacted by the proposed project. The key impacts to be enabled by the proposed project include the broader and significant impact on education, research training, and outreach activities. These impacts will be implemented through (i) curriculum development and enhancement, (ii) active mentorship for undergraduate and graduate students, and (iii) outreach to high school students.

Curriculum Development and Enhancement: The proposed project will directly impact our undergraduate and graduate programs. UM-D offers courses related to advanced mobility and energy systems, including Machine Vision (ECE 488), Robot Vision (ECE 4881, ECE 588), Artificial Intelligence (CIS 479, CIS 579), Vehicle Electronics (ECE 510), Intelligent Vehicle Systems (ECE 531), Auto Sensors and Actuators (ECE 532), All-Weather Automotive Vision (ECE 536), Electric Vehicles (ECE 546), Cyber-Physical System Security (ECE 5544), Artificial Neural Networks (ECE 583), and Pattern Recognition and Neural Networks (ECE 5831). M-ROVER-A will also facilitate new multi- and interdisciplinary courses between Electrical and Computer Engineering (ECE), Robotics Engineering (RE), Computer and Information Science (CIS), Industrial and Manufacturing Systems Engineering (IMSE), and Mechanical Engineering (ME). The new courses that will be developed include In-Vehicular Network Security (CIS, ECE, ME), Vehicular Network Forensics (ECE, CIS), Virtual Reality for Advanced Mobility (RE, CIS, IMSE, ME), Computer Vision for Advanced Mobility (CIS, ECE, RE, ME), Artificial Intelligence for Advanced Mobility Driving (ECE, CIS, ME), and Sensor Fusion for Intelligent Robotics (RE, ECE, CIS).

Mentoring Undergraduate and Graduate Students: M-ROVER-A will help train and mentor undergraduate and graduate students who are interested in advanced mobility, power energy systems, machine learning, and AI. The proposed project will provide crucial hands-on research training opportunities for students who are working in these areas. The PI will advise students through classes, research meetings, conferences, and student competitions. The PI has a strong history of mentoring undergraduate and graduate students. For undergraduate mentoring, the PI participated 2021 Summer Undergraduate Research Experience (SURE) program with a project named "Driver Style Transfer for Autonomous Driving." For graduates and undergraduates, UM-D's Mauto team advised by multiple faculty including PI won 3rd place in categories of Solutions Report, Showcase Booth, and Solutions Presentation in the SAE MobilityForward Challenge: AI Mini-Challenge sponsored by Ford Motor Company in 2021.

Future Workforce: Advanced mobility, mobile robotics, machine learning, and AI are the most demanding areas in America's new industry. Yet, due to the inter and multidisciplinary characteristics of the areas, it has been challenging to train the competitive workforce for the US. As the age of internal combustion engines wanes, the next-generation advanced mobility workforce is required to take multidisciplinary approaches. The proposed project will be able to offer undergraduate, graduate students, and post-doctoral fellows such research training opportunities through experiential learning.

Outreach for High School Students: Classified as a Carnegie Engaged Campus [27] since 2015, UM-D has extensive, long-term partnerships with multiple K-12 school districts across southeast Michigan that primarily serve marginalized communities, including Detroit Public Schools Community District, Dearborn Public Schools, University Prep Schools, and Advanced Technology Academy, among many others. Through our Federal TRIO programs [28] (e.g., MI Gear Up), there will be tremendous STEM exposure opportunities for engaging with teachers and students utilizing the proposed project output for research training purposes, whether on our campus or at the schools themselves. UM-D campus is deeply committed to supporting pathways to higher education for Black, Indigenous, and People of Color (BIPOC) [29] and other marginalized students and envisions this specialized equipment as one more way to excite youth about STEM education and careers.

ERI Criteria

The proposed M-ROVER-A will provide the foundation for scholarly contributions to engineering research by giving an affordable, highly reproducible, and full-featured AI-powered mesoscale electric vehicular platform with a DBW system that can emulate a full-scale research vehicle. Since it is affordable, even with a few amount of research funds, researchers can duplicate the proposed platforms as many as possible. M-ROVER-A will significantly extend the accessibility of highly automated and autonomous mobile robots and vehicles so that a strong foundation for sustained scholarly contributions to engineering research will be established and strengthened.

The proposed engineering research initiation activities will significantly enhance the PI's ability to maintain impactful research activities by giving better opportunities to train undergraduate and graduate students to be researchers for PI's research in machine intelligence. Currently, due to the multidisciplinary aspects of the PI's research, it has not been easy to find a qualified researcher who will be able to conduct PI's research without having an extensive training period. If the proposed project is completed successfully, the PI will have an essential tool to train students to be ready to start productive research. This will enhance the PI's ability to continue impactful research activities.