Indy Autonomous Challenge

PoliMOVE team white paper

The Team

The PoliMOVE team for the Indy Autonomous Challenge is part of the MOVE research team at Politecnico di Milano.

Founded in 1863, Politecnico di Milano is the largest school of architecture, design and engineering in Italy. According to the 2019-2020 QS World University Rankings, Politecnico di Milano is among the top twenty universities (position 16th) in the world in the Engineering&Technology area.

The Dipartimento di Elettronica, Informazione e Bioingengeria (DEIB) is one of the largest European ICT departments. With nearly 1000 members, researchers, collaborators, PhD students, technical and administrative staff, the Department is a vital institution capable of promoting education, fundamental and applied research, and technology transfer to companies. DEIB shares with the Politecnico di Milano a strong commitment to cooperating with the industry and with the society, and the effort to bring real world's problems closer to the academic research. DEIB researchers engage both in long-term research activities and in applied research projects targeted to the immediate industrial exploitation. Today DEIB is a leading contributor in terms of delivered patents, spin-offs, and incubated companies.

Within DEIB, the research group MOVE (https://www.move.deib.polimi.it/), is one of the leading international groups in the field of vehicles-control. Founded in 2001, the MOVE research team is constituted by 6 Faculty members, more than 20 PhD students, and more than 50 MSc students. The group is chaired by its founder, Prof. Sergio M. Savaresi (https://www.linkedin.com/in/sergio-m-savaresi-74b55ba/).

MOVE is fully focused on Automation&Control in vehicles, with a vast experience on:

- Different TYPES of vehicles (e-Bikes, motorcycles, cars, off-highway vehicles, etc.)
- Different LAYERS of systems and control technologies (smart actuators and smart sensors, virtual sensors, braking control, traction control, stability control, electronic-suspensions control, control and optimization of electric and hybrid vehicles, ADAS and navigation control of semi-autonomous/autonomous vehicles, etc.)

In the last 5 years, the MOVE research group:

- Has developed more than 150 research projects in cooperation with leading companies (among which: Ferrari, Lamborghini, Maserati, AlfaRomeo, JaguarLandRover, Ducati, Aprilia, Piaggio, KTM, Yamaha, Brembo, Magneti-Marelli, Bosch, Huawei, etc…), on advanced &RD projects at different TRL (in the range TRL4-TRL8).
- Has published more than 150 scientific papers at international level
- Has filed more than 50 patents
- Has originated the foundation of 10 spinoff companies, mostly in the field of vehicular technologies (among them: https://www.e-shock.it/rob-y/, https://blubrake.it/, https://www.yapemobility.it/, http://hiride.bike/, http://www.zehus.it/, etc.)

The core team for the Indy Autonomous Challenge is:

- Prof. Sergio M. Savaresi (https://www.linkedin.com/in/sergio-m-savaresi-74b55ba/)
- Prof. Matteo Corno (https://www.linkedin.com/in/matteo-corno-2935842/)
- Prof. Giulio Panzani (https://www.linkedin.com/in/giulio-panzani-a103421a4/)
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- 1st year PhD student (MSc in Automation Eng.) Stefano Radrizzani (https://www.linkedin.com/in/stefano-radrizzani/)

All the team members are highly specialized (with different levels of seniority and different types of specific expertise) on Automation&Control in vehicles and vehicular systems.

Team Management

Due to the long-lasting experience in R&D projects in cooperation with Companies, and in the development of products in start-ups, the PoliMOVE team is highly skilled to manage complex and challenging projects.

The PoliMOVE team is organized as follows:

- Team Manager: Prof. Sergio M. Savaresi
- Team Technical Leader: Prof Matteo Corno, supported by prof. Giulio Panzani (Deputy Technical Leader)
- Phd-Students Leader: Filippo Parravicini, supported by Gianluca Papa (Deputy PhD-students Leader)

This core management and technical team will coordinate the activities of a large group of multi-disciplinary PhD students with complementary skills and expertise, with the additional support of MsC students (to be defined along the project)

Fundraising

The MOVE research group already has a large self-funding capacity, that can fully support the team over the whole Indy Autonomous Challenge, for all the related expenses (PhD scholarships, travels, SW licenses, etc.). However, thanks to its vast network of Industrial Partners, the PoliMOVE team will find some sponsorships to further support the team in the Indy Autonomous Challenge and to reinforce its industrial network.

Software Development Plan

The generation of the autonomous driving software in the context of racing cars will exploit the team expertise in all the areas involved in this task, ranging from high-level navigation down to low-level vehicle dynamics control. The algorithmic architecture, which will be detailed in the following sections, will mirror the classical autonomous driving paradigm by including modules for Mapping and Localization, Global Trajectory Planning, Local Trajectory Planning and Trajectory Tracking with Vehicle Dynamics handling. Our hypothesis on the underlying hardware architecture, especially in terms of available ECUs are also reported. Our plan envisages the use of advanced software development tools together with industry-grade simulation environments for algorithm development and preliminary testing. Moreover, according to our standard breakdown structure, we plan to include a hardware-in-the-loop testing phase, followed by real-world testing for some of the modules on benchmark platforms and test vehicles. Once the official simulator is available, we will deploy the designed algorithms in the prescribed software framework and start with final testing and refinement.

Automated Vehicle Software Architecture

In order to solve the task of developing a racing-capable autonomous driving algorithm, a layered control structure will be developed. The main modules will deal with Mapping and Localization, Global Trajectory Planning, Local Trajectory Planning and Trajectory Tracking with Vehicle Dynamics handling.

Mapping/Localization

The first critical task to be tackled in autonomous driving is that of precisely localizing the vehicle on the track. Depending on the final sensor setup of the racing car, we envisioned three possible approaches to deal with localization. If high frequency and high precision localization measures (RTK GPS or similar), together with proprioceptive sensor readings are available, we will cast the problem into a sensor fusion frame. In this case, filtering techniques (Extended Kalman Filter/Unscented Kalman Filter or similar) will be used alongside the knowledge on the vehicle dynamics to reconstruct the best estimate of the vehicle pose. Should the GPS precision be deemed insufficient to safely and efficiently drive the vehicle, an alternative approach that leverages cameras will be implemented. In this case, GPS and sensor fusion will be utilized to provide a rough estimate of the vehicle position along the track; then, image analysis techniques will be used to refine the vehicle pose within the track boundaries [1]. Finally, if none of the previous is applicable, our plan is to apply our expertise in the mobile robotics field to implement a map-based localization algorithm [2][3]. In this case too, our choice will be affected by the actual available sensor suite. In particular, if a sufficiently dense 3D lidar is available either AMCL or Graph SLAM localization would be an effective solution. On the other hand, if high resolution cameras are available together with a reasonable computational power, a Visual SLAM approach could also be adopted.

Global Trajectory Planning

Once a sufficiently precise estimate of the vehicle pose in the track is made available by the localization module, the next problem to be solved requires the generation of a desired trajectory for the vehicle to follow. The traditional scheme for autonomous driving splits the problem into two subproblems. The first one consists in the generation of a trajectory over a medium-long time horizon that allows the vehicle to travel from the actual position to the desired goal. The second regards the definition of a short-term trajectory that allows the vehicle to cope with specific tasks such as obstacle avoidance or, in case of a race, overtake maneuvers. With a slight abuse of the terms we will refer to the first as Global Planning and to the second as Local Planning. Since the race takes place in a predetermined and known track, the global planning step focuses on the relatively simpler task of determining the trajectory that allows to perform a full lap in the minimum time. In particular, the best trajectory in terms of traveled distance could easily be computed offline, based only on geometrical information about the Indianapolis Track and on the vehicle handling capabilities. However, since the optimal trajectory can strongly vary based on the track and meteorological conditions at race time, we plan on developing an ad-hoc optimization strategy to design an optimal global trajectory which accounts for the actual handling capabilities of the vehicle at race time.

Local Trajectory Planning

The output of the global trajectory planning algorithm will be a sequence of points in a global reference frame describing the time optimal trajectory for the vehicle. However, during the race, the vehicle has to cope with the presence of other vehicles and potential obstacles in the track, so that in general, it will be impossible for it to follow the global trajectory at all the times. A local trajectory planner will therefore be included with the intent of generating a refined, local trajectory which aims at following the global trajectory as much as possible while guaranteeing obstacle avoidance. The general approach to local planning will involve an environment sensing and obstacle detection phase, followed by a maneuver selection module to end with a trajectory generation and optimization algorithm. As far as sensing is concerned, our choices will be guided by the specific sensor availability as well as by the overall computational power of the supplied ECUs. In particular, if cameras are the sensor of choice, we will exploit our previous experience in the application of computer vision techniques to the automotive field [1][4][5]. On the other end, if at least one Lidar/Radar sensor is provided, we will leverage the knowledge of obstacle detection and extended-target tracking algorithms in order to provide a real time estimation of the position and speed of the other vehicles on the track [6][7][8][9]. In both cases, the sensing phase will be enhanced using V2V or V2I communication, if available [10]. Starting from the output of the environment sensing modules, a maneuver manager will be designed to determine the correct maneuver at each time instant (e.g. “keep the course”,” overtake”,…). In this respect we will leverage our previous experience with emergency maneuvers in automated passenger vehicles (such as emergency lane change) [11][12]. These are particularly critical for two reasons: they involve operating close to the handling limits, and they require a fast lateral motion of the vehicle. As such, we expect our algorithms to be easily extended to the case of a racing car, for which similar handling requirements need to be met. In particular, our algorithms are capable of quickly providing obstacle avoiding trajectories which are guaranteed to reach the limits of the vehicle handling while also considering the tracking capabilities of the underlying trajectory tracking module. Finally, as any human racer could testify, the optimal trajectory for the car at each instant is strongly dependent on many factors, such as tire wear and temperature, etc. As such, the minimum lap-time trajectory could vary from lap to lap. In order to cope with this, local trajectories (both in presence and in absence of other vehicles or obstacles on the track) will be optimized with respect to the estimated tire-to-road interaction in each point of the track [13],[14],[15],[16].

Trajectory Tracking

The final step of the autonomous driving algorithm involves the generation of the control commands to be sent to the actuators in order to make the vehicle perform the prescribed trajectory, defined from the combination of local and global planning, in the best possible way. The defined trajectory will consist, in its most general definition, of a sequence of poses optimized with respect to vehicle handling capability. The main goal is that of winning a race, hence the generated trajectory is also expected to require the vehicle to operate as close as possible to its handling limits. As such, trajectory tracking requires a profound knowledge of the vehicle dynamics, together with the ability to estimate the vehicle state as precisely as possible. In particular, the most critical variable to be estimated when dealing with trajectory tracking consists of tire longitudinal slip and side-slip angle and road tire forces. The longitudinal slip is involved in the longitudinal dynamic and precisely it plays a central role in braking and traction control. In the last decades, our research group, has successfully developed methods for the estimation of this quantity on different means of transportation and by using multiple sensor combination [17]. Analogously to the longitudinal case, in lateral dynamic the side slip angle plays a crucial role and its estimation and control guarantee the correct handling of a curve. Our research group has experience in the development of reliable means for the estimation of the side slip in different automotive scenario [13],[14],[15],[16]. Given a precise and reliable estimation of these quantities, either classical feedback control techniques or Model Predictive Controllers (MPC) can be applied to control the lateral and longitudinal dynamic and hence handle the prescribed trajectory. We found MPC to be particularly suited to the autonomous driving context thanks to its optimality properties; as such, depending on the vehicle design and on the available ECU computational power, this is likely to be our first candidate for the tracking module control algorithm. In years of collaboration with automotive OEMs, our research group has also worked on various advanced longitudinal and lateral control techniques such as torque vectoring, ABS and traction control. Our algorithms proved to be effective on different actuator means (brake by wire, differential braking, four-wheel steering) which would make our target tracking algorithm robust to most of the design choices that are still to be made on the final competition vehicle [18]-[33].

Actuation

Our software development plan builds on the hypothesis that the vehicle is equipped with set of smart actuators capable of tracking the physical input references commanded by the trajectory tracking modules. Even if this not the case, our team has a longstanding experience in developing the required actuator-level control algorithms. In particular, as is common when dealing with vehicle dynamic control, we suppose the physical input to the system to consists of steering (in the form of differential braking and/or actual wheel steering), braking and traction torque. The goal of the actuators control modules would be that of tracking the reference signals for the control variables i.e. the steering angle or the braking and traction torque for each wheel, computed by the trajectory tracking module. Due to the challenging context of racing cars, we expect efficiency and precise tracking to be of paramount importance. In this respect, our team can leverage previous work experiences with multiple racing automotive companies, in which the final aim was that of developing high-performance solutions for different actuation technologies [34], [35], [36], [37].

Automated Vehicle Hardware Architecture

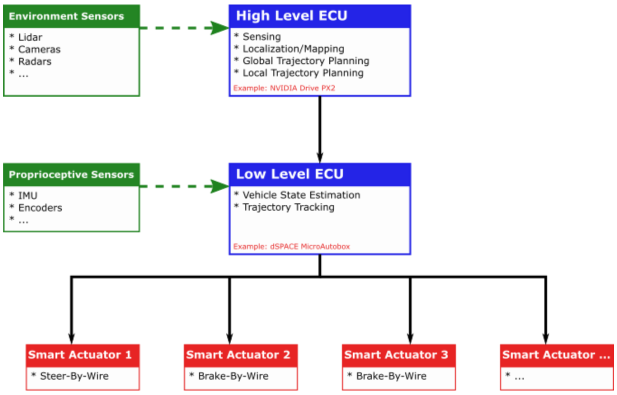

Figure 1: ECU connections hypothesis

While being fully aware of the needs for a standardized hardware for all the teams, we would like to sketch a possible draft of the control-hardware architecture. The involved ECUs and their connections are reported in Figure 1. According to this scheme, all the high-level automation task would be implemented in a power efficient embedded computing board. Mapping, localization, trajectory planning together with all the sensing task associated with high information-density sensors would be implemented at this level. The corresponding ECU should provide relatively high computational power, parallel computing capabilities (GPU-like) and high abstraction programming language compatibility. Concerning this type of ECUs our team has had previous experience with NVIDIA platforms such as Jetson Tx2 and Drive Px2. Any comparable hardware with Ubuntu capabilities would easily replace this choice. As explained in Figure 1, lower level ECU should be in charge of Trajectory tracking and vehicle state reconstruction. We have indicated dSPACE MicroAutobox as the hardware we have experience with, but any comparable platform would also be suitable. Finally, as explained in the previous section, we imagine the vehicle to be equipped with smart actuators. No hypothesis was made on such actuators at this level except for their compatibility with the I/O interface of the above ECU.

Simulation and Testing Plan

. The simulation and testing phase will first address each single algorithm module (e.g. perception, mapping, localization, planning and tracking); in a second phase the overall algorithm will be completely verified. The single modules of the algorithm will be firstly tested in a simulation environment and then on a real platform to ensure the functioning of the specific subsystem. Specifically, the testing procedure for each component consists of three interconnected steps; in sequence: software simulation, hardware sensor in the loop simulation and real system simulation. The main element necessary for both the software and hardware in the loop simulation phase consists in an accurate model of the vehicle which must include sensors, hardware and actuator components. Different environment can be used for vehicle as well as its associated component modeling and these encompass, Simulink, Simscape, CarMaker, VI-CarRealTime and others. During the past years we have faced different modeling and simulation challenges which, have not only helped us to develop know how on multiple simulation environment, but also to understand how to select the specific environment depending on the simulation problem to be addressed.

STEP1: Software simulation

Given the vehicle, the track and the associated sensors, actuators and hardware components we are able to reproduce them in an accurate and reliable form and create a test bench where the single modules as well as the overall autonomous driving algorithm can be safely and repeatedly tested.

STEP2: Hardware in the loop

In a second phase the simulation environment will be further integrated with real sensor and hardware which will be mounted on the real vehicle to create a realistic hardware/sensor in the loop simulation. This simulation phase is useful to verify the functioning and integration of the different interconnected modules of the algorithm when running on the real hardware. Different hardware components will be tested. Indeed, each algorithm module will run on its associated hardware. Considering the previously architecture scheme in Figure 1, then the algorithm for perception, mapping, localization and planning will run on the NVIDIA (PX2 or Jetson) while that for tracking module will run on the dSPACE MicroAutobox.

STEP3: Real system simulation

The single module *i.e.* perception, mapping, localization and planning will be further separately and interconnected tested. Matter of fact, the resources of the research group include both experimental vehicle and testing devices which will be used to characterize the modules on a real driving scenario.

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Technical Overview and Plan for the Indy Autonomous Challenge (IAC)

Michigan State University – The CANVAS Initiative

Introduction

The Indy Autonomous Challenge (IAC) represents a unique and arguably historic opportunity for Michigan State University (MSU) and other academic institutions to advance autonomous system research in unprecedented way[1]. The impact of IAC could be far reaching many years or even decades beyond the anticipated initial years, 2020 – 2021, of the competition. In this document, we highlight MSU's capabilities and level of readiness in the area of autonomous vehicles. We also provide a high-level description of our technical approach for participating in IAC.

MSU's Research Capabilities in Autonomous-Vehicle Research

The College of Engineering at Michigan State University is among the largest engineering colleges nationwide with enrollment of more than 7000 students in the 2019-2020 academic year[2]. With nine departments, including Electrical and Computer Engineering, Computer Science and Engineering, Mechanical Engineering, Civil and Environmental Engineering, Chemical Engineering, and the newly formed Computational Mathematics, Science, and Engineering (CMSE), the college is well positioned as a leader in the education, training, and preparation of engineers for the future of the automotive industry and mobility. Equally important is MSU's world-renowned faculty members and research programs that at the core of autonomous driving technology areas. The areas where MSU developed international reputation and strong pedigree over the past five decades include computer vision, pattern recognition, machine learning, deep learning, image processing, signal processing, radar, antenna, sensor networks, and software engineering.

Due to its strong expertise and knowledge base in autonomous-driving related disciplines, MSU established a world-class initiative: CANVAS – Connected and Autonomous Networked-Vehicles for Active Safety. CANVAS includes more than 20 faculty members engaged in different research areas of autonomous and connected vehicles, three members of the National Academy of Engineering (NAE) and nine Fellows of the SAE/IEEE/ACM. Equally important, the CANVAS initiative has attracted talented undergraduate and graduate engineering students toward the

[1] https://www.indyautonomouschallenge.com/history

[2] https://www.egr.msu.edu/news/2019/08/26/welcome-2019-20

area of autonomous driving. This led to the formation of a CANVAS student club, where undergraduate students are volunteering and enthusiastically collaborating to explore technical challenges and solutions for autonomous driving under the mentorship of MSU engineering faculty.

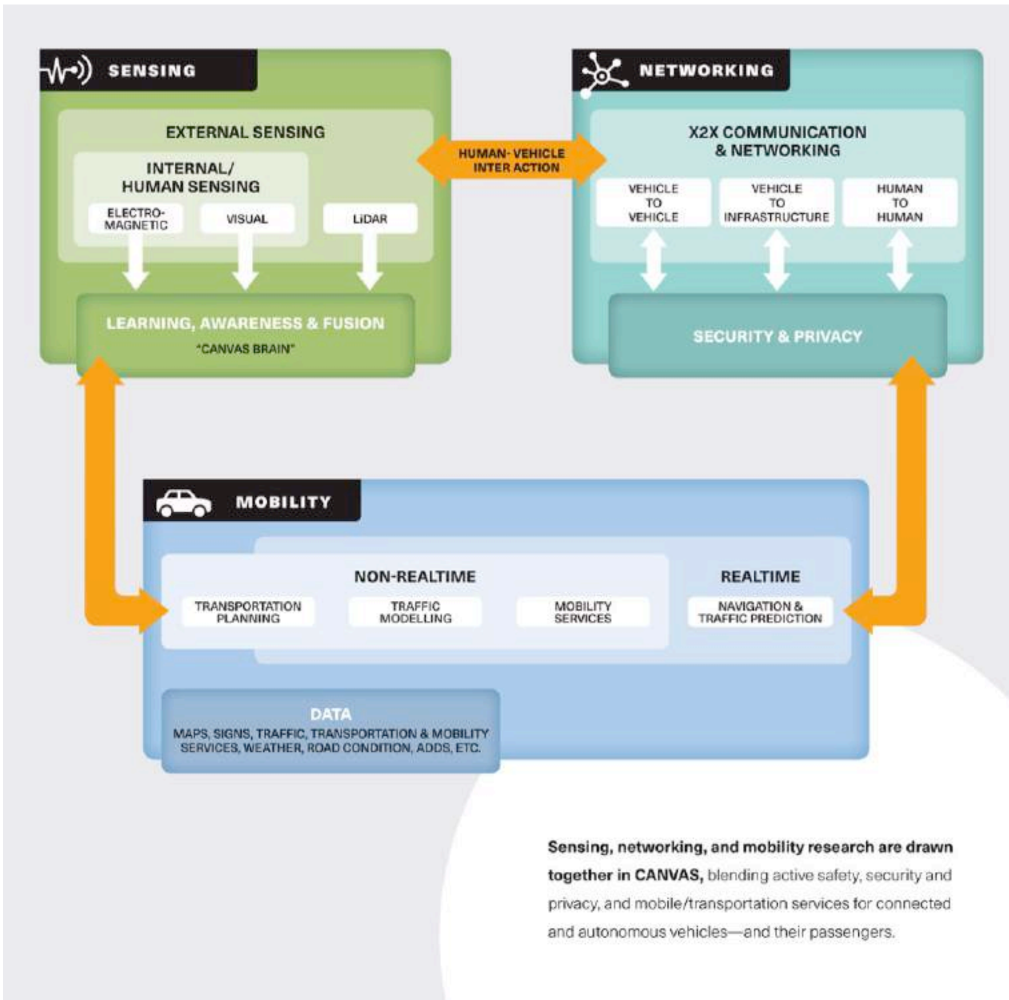
In addition to being located within the state of Michigan, which is the nation's center for R&D in automotive engineering, the College of Engineering at MSU has many centers of excellence, national centers, and laboratories that students and faculty working in the area of autonomous driving can draw expertise from. This includes the Composite Vehicle Research Center (CVPR), Energy and Automotive Research Lab (EARL), the US Department of Transportation Center for Highway Pavement Preservation (CHPP), National Science Foundation Center for Evolutionary Computing (BEACON), and many others.

The CANVAS Research Program

CANVAS is built on decades of MSU faculty expertise and world-renowned research in key areas for autonomous vehicles, including electromagnetics, computer vision, machine learning, deep learning, image and signal processing, pattern recognition, and sensor fusion. Moreover, CANVAS is a comprehensive initiative integrating broad research areas in autonomy, connectivity and mobility as shown in Figure 1.

In the context of autonomous research, an important focus of the CANVAS initiative is on the development and integration of advanced solutions for high-precision sensing of autonomous vehicles' environments. In particular, our focus has been on three sensing modalities: Radar/mm-wave based sensing, visual sensing, and LiDAR sensing. Both external and internal/human sensing are being pursued. A crucial aspect of our research is the fusion of these sensing modalities in conjunction with advanced artificial intelligence solutions based on machine learning and novel deep learning architectures and models. Below, we provide a brief overview of selected research activities as an example.

(a) **Radar and Electromagnetics**: Electromagnetic waves-based sensing in the form of radar signals with a variety of short- medium, and long-range scanning and comprehensive 360-degree coverage around autonomous vehicles represents a cornerstone research area of the CANVAS initiative. Besides exploiting state-of-the-art in autonomous radar sensing solutions, the EM Research Group (EMRG) at MSU, and with more than 100 years of combined expertise of current research-active faculty, have established solid foundations in many EM areas that are crucial for autonomous and connected vehicle research. These areas include antenna design and integration over frequency spectrum up to the terahertz (THz) range, EM Interference and Compatibility (EMI/EMC), high-frequency silicon electronics, and materials characterization. While the early stages of the CANVAS effort is exploiting current state-of-the-art radar sensing solutions (e.g., over the 77 GHz frequency spectrum) to develop an early prototype for an autonomous vehicle, the CANVAS EM group is pursuing advanced research that will perfect current solutions, increase radar signal resolutions in time and space, achieve reliable sensing under extreme conditions, and integrate various autonomous and connected vehicle EM technologies. More importantly, a crucial objective of this research is to reduce cost, power consumption, interference, and the hardware footprint that these advanced EM solutions require while perfecting the active-safety performance of autonomous vehicles.



Sensing, networking, and mobility research are drawn together in CANVAS, blending active safety, security and privacy, and mobile/transportation services for connected and autonomous vehicles—and their passengers.

Figure 1: The CANVAS Architecture

(b) **Visual Sensing**: Visual sensing represents another cornerstone component of the CANVAS initiative. With world-renowned faculty and labs in the areas of computer vision, pattern recognition, machine learning, video scene analysis, video communications, and image processing, the CANVAS team has been developing high-precision solutions for a variety of object recognition, detection, and tracking applications. These solutions are pivotal for detecting and tracking pedestrians, animals, cyclists, and other vehicles, assessing weather and road conditions, and issuing lane departure warning for semi-autonomous driving. It is crucial to highlight that under CANVAS, visual sensing related research is being pursued in synergy with research activities in the radar area to achieve robust, smooth, and highly precise operation of autonomous vehicles. Additionally, the CANVAS visual research group is building on state-of-the-art in automated driver monitoring applications such as drowsiness detection, age and gender estimation from face images for customized analysis and response, gesture and posture analysis, cognitive and emotion assessment, and driver personalization. Furthermore, the group has experience in processing images and videos acquired either in the visible spectrum or infrared spectrum, including thermal images. We are also fully cognizant about the necessity for developing solutions targeted at the transition period toward full autonomous driving. For this transition period, it is pivotal to integrate solutions that are mindful of the driver's needs and conditions. In that regard, we have developed an array of algorithms for facial landmark tracking, head pose estimation, facial expression analysis, hand tracking, and body gesture analysis. Given a camera pointing at the driver, these algorithms can be applied to analyze the behavior and emotional state of the driver for customized response to road conditions.

(c) **Lidar Sensing**: In the lidar area, we are developing robust solutions for maintaining a 3D, dynamically varying, local environment map surrounding a vehicle. In addition to employing Lidar sensing for navigating the vehicle around different obstacles, we have developed Lidar-based approaches for localization[3] and mapping[4]. Achieving this requires robustly detecting nearby vehicles, estimating and tracking their poses, and making predictions of their future trajectories. In addition, novel solutions for employing advanced lidar models of a variety of objects are being pursed for robust classification. Fusion of lidar data with other sensing modalities for more robust detection and classification of objects is also being pursued.

(d) **Deep Learning and Sensor Fusion**: Under deep learning and sensor fusion, a critical module of the CANVAS initiative is the "CANVAS Brain" engine, where a broad range of advanced algorithms are being realized[5]. This engine represents both the training aspects of autonomous vehicles in addition to realtime decision-making algorithms. Each sensing modality (radar, visual, and lidar) has its own optimized algorithms for recognizing and tracking a

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[3] S. Pang, D. Kent, X. Cai, H. Al-Qassab, D. Morris and H. Radha, "3D Scan Registration Based Localization for Autonomous Vehicles - A Comparison of NDT and ICP under Realistic Conditions," *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*, Chicago, IL, USA, 2018, pp. 1-5. doi: 10.1109/VTCFall.2018.8690819

[4] S. Pang, D. Kent, D. Morris and H. Radha, "FLAME: Feature-Likelihood Based Mapping and Localization for Autonomous Vehicles," *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Macau, China, 2019, pp. 5312-5319.doi: 10.1109/IROS40897.2019.8968082

[5] M. Al-Qizwini, I. Barjasteh, H. Al-Qassab and H. Radha, "Deep learning algorithm for autonomous driving using GoogLeNet," *2017 IEEE Intelligent Vehicles Symposium (IV)*, Los Angeles, CA, 2017, pp. 89-96. doi: 10.1109/IVS.2017.7995703

variety of objects surrounding the vehicle. A crucial aspect of the CANVAS initiative is the acquisition of an extensive and massive amount of data, on a continuous basis, for each sensing modality under a wide range of traffic and weather conditions. This massive data will be continuously collected and used to train and tune advanced machine-learning algorithms, deep, and popular convolutional learning neural networks. The CANVAS Brian engine also uses data from the Mobility component of CANVAS, which includes highly-accurate positioning data, maps, and related navigation information. Collectively, all of the sensed and navigation data are optimally diffused to guide the autonomous vehicle and determines its realtime action.

(e) **Planning and Control:** Under this area, CANVAS faculty and students are exploring advanced approaches for global and local path planning and novel control algorithms for guiding autonomous vehicles toward following the planned paths. In particular, one area of research focus is on developing robust path following control frameworks for of self-driving vehicles operating under mismatched perturbations due to the effect of parametric uncertainties, vehicle side-slip angle, and road banking. This form of research could be pivotal for a autonomous racing scenarios such as the ones envisioned for the IAC competition.

(f) **Connectivity:** Vehicle-to-vehicle connectivity represents another area where CANVAS faculty and students have made some key contributions. This includes developing some of the fundamental technologies and protocols in the early areas of vehicle networks[6] (VANETs). More recently, we have been exploring advanced sensor fusion among connected vehicles for improved safety[7]. This includes a novel framework for sharing visual data between connected vehicles in scenarios where certain objects are not in the field-of-view of a given vehicle, while the same objects could be viewed and detected by other vehicles within the same network[8].

High-Level Technical Plan for IAC

The Indy Autonomous Challenge will require unprecedented solutions for autonomous driving at ultra-high-speed (UHS) that could exceed 200 mph, and at a minimum speed of 100 mph as stipulated by the competition rules. At such UHS, many of the conventional

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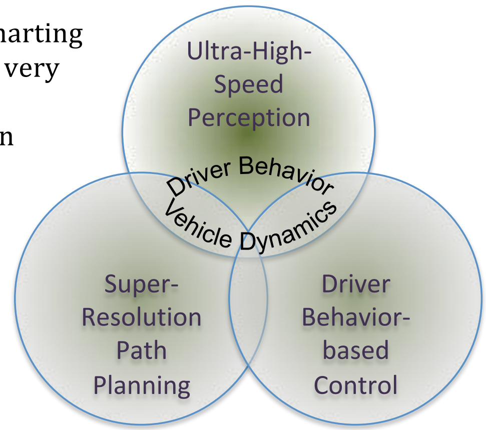
[6] S. Biswas, R. Tatchikou and F. Dion, "Vehicle-to-vehicle wireless communication protocols for enhancing highway traffic safety," in *IEEE Communications Magazine*, vol. 44, no. 1, pp. 74-82, Jan. 2006. doi: 10.1109/MCOM.2006.1580935

[7] Al-Qassab, H., Pang, S., Al-Qizwini, M., Kent, D. et al., "Active Safety System for Connected Vehicles," *SAE Intl. J CAV* 2(3):191-200, 2019, https://doi.org/10.4271/12-02-03-0013.

[8] Al-Qassab, H., Pang, S., Al-Qizwini, M., and Radha, H., "Visual Sensor Fusion and Data Sharing across Connected Vehicles for Active Safety," SAE Technical Paper 2018-01-0026, 2018, https://doi.org/10.4271/2018-01-0026.

technologies will either be obsolete or incapable of handling the environment in terms of perception, planning and control. Consequently, new design frameworks and corresponding algorithms will be needed for IAC. Key aspects of these new solutions include:

(1) Ultra-High-Speed Perception that enables the vehicle to detect static and dynamic objects, most notably other racing vehicles in the environment. This will require development of novel sensor-data processing and fusion techniques that must operate in real-time at UHS.
(2) Super-resolution Path Planning that is capable of charting multi-scale and multi-resolution paths that require very rapid updates in real-time.
(3) Driver-Behavior-based Control that will be based on thorough analysis of professional racecar drivers' comprehension, planning and control of the vehicle.
(4) Vehicle Dynamics analysis and simulation will be of paramount importance. This will be accomplished utilizing an industrial-grade vehicle simulation environment that will be provided by ANSYS[9]. The vehicle simulation will capture the full dynamics of the actual Dallara IL-15 Indy Lights that have been redesigned for the competition to accommodate a set of sensors to be mounted on the vehicle.
(5) Professional Racecar Driver Behavior analysis represents another pivotal area for a successful completion of the competition. In essence, the vehicle must learn from a professional racecar driver and not from an average vehicle driver. There have been many studies showing clear differences between professional racecar and novice drivers in terms of reaction time, cognitive aspects of perceiving the environment, planning the next move, and controlling the vehicle.



Conclusion

The CANVAS initiative at MSU has been developing advanced frameworks and solutions for autonomous vehicles for many years. This program positions MSU as a leading contender for participating in the Indy Autonomous Challenge. MSU's readiness is also evident due to the invaluable experience that MSU's students and faculty have gained through their participation in the SAE/GM AutoDrive Challenge. MSU's readiness is also evident when considering the availability of two autonomous-vehicle platforms equipped with state-of-the-art sensing devices and computers capable of performing complex deep learning and related algorithms in real-time. Consequently, the MSU team is looking forward to participating in the IAC historic competition.

[9] https://www.ansys.com/products/systems/adas

Crimson Autonomous Racing (CAR)

The Crimson Autonomous Racing (CAR) team in based at the University of Alabama, at Tuscaloosa Alabama. The team is comprised of faculty, graduate students and undergraduate students with the goal of competing in collegiate autonomous motorsports competitions. The goals of the team are to enhance learning for the students and create research opportunities through demonstration of capabilities in the crucible of motorsports.

The Competitions

The team has entered the 2020 Autonomous Division of the Purdue University evGrandPrix and is entering the Indy Autonomous Challenge.

2020 evGrandPrix

CAR has acquired the specified kart and drivetrain for the 2020 evGrandPrix. The team has chosen the nVidia Xavier computing platform and has designed a sensor package to use on the kart. The sensor package has been acquired and includes a Velodyne Puck lidar, an Intel RealSense camera. The team has assembled the kart and testing will begin soon. Custom software for the nVidia Xavier is being designed and developed by the team.

Indy Autonomous Challenge

The team is excited to enter the Indy Autonomous Challenge. The event promises to be exciting and spectacular. The specific challenges that occur in motorsports competition, especially at the Indianapolis Motor Speedway, should foster creativity and new solutions to problems in the autonomous vehicle research arena. Our team would very much like to be a part of the collaborative environment that this competition desires.

Experience

The University of Alabama has been involved in several relevant student competitions. The successes in these competitions show the ability of our students and faculty to organize and lead, as well as demonstrate the technical competence required.

EcoCAR

In Spring 2014, the UA team was selected to compete in a four-year competition named EcoCAR 3 starting in Fall 2014. EcoCAR 3 was US Department of Energy (DOE) Advanced Vehicle Technology Competition (AVTC) series and was North America's premier collegiate automotive engineering competition. The US DOE and General Motors challenged 16 North American universities to redesign a 2016 Chevrolet Camaro into a hybrid-electric car that reduces environmental impact, while maintaining the high performance expected from the car. Throughout the four-year competition, the UA team won numerous awards, and finished as the third team in the final year.

After successful completion of EcoCAR 3, the UA team was selected again to compete in another four-year competition starting in 2018. The competition named as the EcoCAR Mobility Challenge (EcoCAR) is the latest U.S. Department of Energy (DOE) Advanced Vehicle Technology Competition (AVTC) series. The four-year competition will challenge 12 university teams to apply advanced propulsion systems, as well as connected and automated vehicle technology to improve the energy efficiency, safety and consumer appeal of the 2019 Chevrolet Blazer – Specifically for the carsharing market. Headline sponsored by DOE, General Motors (GM) and MathWorks, and managed by Argonne National Laboratory, EcoCAR is the heart of automotive ingenuity working towards future mobility solutions.

Formula SAE

Formula SAE aims to develop better engineers by providing hands-on experience in which students design, construct and compete with an open-wheeled formula-style race car. The University of Alabama's Formula SAE program, known as Crimson Racing, was founded in 2004. The team experienced varying degrees of success during its first ten years; however, since 2015 the engineering sophistication incorporated into the vehicle and the management of the team has steadily and substantially increased. These improvements have been reflected in the size of the team, the engineering abilities of its members and ultimately in the results in the flagship international competition held at Michigan International Speedway. During this time, the team grew from approximately 10 to more than 30 active members, and the finishing place improving each year- starting at 105th in 2015 and culminating in a 10th place finish this past year 2019. The tenth place finish represented the fifth best performance by a domestic university and was highlighted by a seventh place finishes in design and business plan.

In addition to meeting the challenge of designing, building and competing with the current year's vehicle, Crimson Racing embraces its responsibility to inspire and motivate future generations of elite engineers through community outreach. This responsibility has been met through STEM support programs such as SAE's Learn Twice, and NSF STEM Diversity Initiatives as well as supporting engineering promotional activities on campus and at local schools and community colleges.

The Team

The Crimson Autonomous Racing team is composed of faculty and students from the University of Alabama. There are currently 4 faculty members, evenly divided between the Computer Science Department and the Mechanical Engineering Department. There are three graduate students committed to the competition, with two from computer science and one from mechanical engineering, and several undergraduate students have expressed a desire to be a part of the competition.

Dr. Brandon Dixon

Dr. Dixon is an Associate Professor of Computer Science at the University of Alabama. He has conducted research in a wide range of topics including algorithms and data structures, cryptography, software engineering. He currently has ongoing work in the motorsports simulation area, particularly simulation that incorporates vehicle dynamics, and is directing a Ph.D. student in this area.

Dr. Dixon has a long record of experience in open wheel racing at both the amateur and professional level. He has been building, engineering and racing single seat open wheel cars since the early 1990s. His successes include two SCCA amateur road racing national championship wins at the 2010 and 2012 SCCA Runoffs in the FB (F1000) class, and two championships in 2017 and 2019 in the F2000 Championship Series, a competitive professional series for Formula 2000 single seaters. All of these championships are as both a driver and designer/engineer in cars that he had significant contributions to the design and manufacturing effort.

His computer science academic background and extensive motorsports experience put him in a unique position to contribute to the competition.

Dr. Travis Atkison

Dr. Atkison is an Assistant Professor of Computer Science and the director of the Digital Forensics and Control Systems Security Lab (DCSL) at the University of Alabama. His current research efforts focus on the topics of cyber security and transportation infrastructure. These efforts include malicious software detection, threat avoidance, digital forensics, and security in control system environments directed toward transportation. Prior to joining the faculty at the University of Alabama, Dr. Atkison spent several years in academia as well as 7 plus years at the National Security Agency in both the Signals Intelligence and Information Assurance Research Directorates. His work has spanned a wide range of topics, including computer security using both static and dynamic methods, cyber security, information assurance, network security, control system security, transportation infrastructure security, intrusion detection, information retrieval, data mining, distributed data mining, ensemble and hierarchical modeling, and architecture and application development.

Dr. Atkison has a number of years of research experience in the safety and security of control systems. This work has produced more than 10 journal and conference papers on security mechanisms in control system environments.

Dr. Paul Puzinauskas

Dr. Puzinauskas currently serves as an Associate Professor in Mechanical Engineering at The University of Alabama in Tuscaloosa. He was born in Washington DC and received his BS degree in Mechanical Engineering from The University of Maryland, and his MS and Ph.D. degrees also in Mechanical Engineering from The University of Michigan. He currently teaches Internal-Combustion Engines, Combustion, Thermodynamics, Heat Transfer and Experimentation courses and conducts internal-combustion engine, combustion, and instrumentation research. In addition to his research and teaching duties, Dr. Puzinauskas is the Mechanical Engineering Department's Student Projects Coordinator and is the lead faculty advisor for UAs EcoCAR and Formula SAE student competition programs.

Currently, Dr. Puzinauskas and his students are working on a variety of IC engine challenges, including optical diagnostic applications to study air flows and injection sprays and their influence on combustion. The IC engine work includes facilitating advanced combustion strategies to improve efficiency and emission performance, developing low-emission small engines, improving transient control and optimizing IC engines for hybrid-electric-vehicle applications. The optical diagnostic applies include laser-induced breakdown spectroscopy (LIBS), laser-induced incandescence (LII), particle-image velocimetry (PIV) among others.

Dr. Puzinauskas' role as Student Projects Coordinator manifests through course development, enhanced extra-curricular training facilitation and fundraising and project management support. He has offered Engineering Leadership for the last 11 consecutive semesters. This is a course he developed through collaboration with the Culverhouse Business School and various industrial sponsors with the objective to improve management, motivational and development skills among the students in leadership positions of UAs various engineering competition teams. Part of the student's academic responsibilities participating in this course include development and presentation of on-campus weekend engineering workshops. These workshops are available to the College's students and provide training in extra-curricular skills such as manual and automated manufacturing, welding, finite element analysis, modeling and simulation as well as management and financial development.

Dr. Hwan-Sik Yoon

Dr. Yoon is an Associate Professor of Mechanical Engineering at the University of Alabama. His general research interests include modeling, simulation, and control of dynamic systems. His current research efforts are focused on vehicle powertrain systems, hybrid electric vehicles, connected and autonomous vehicles, and application of machine learning in automotive engineering. Some of the exemplary projects that he is currently involved in include component time-to-failure prediction using NARX network, traffic route optimization using reinforcement learning, and hybrid electric vehicle control using reinforcement learning. From 2014 to 2018, Dr. Yoon served as an advisor for the modeling and simulation subteam in the UA EcoCAR3 team and is currently an advisor for the connected and automated vehicles subteam in the EcoCAR mobility challenge team. Dr. Yoon won 2019 NSF Outstanding Faculty Advisor Award for his service in the UA EcoCAR team.

Cole Frederick

Cole is a third-year graduate student in computer science. He has a passion for motorsports that has continued to shine through college. He joined the Formula SAE as a freshman and became the team captain for the next four years of his mechanical engineering undergraduate degree taking the team from 98th to 17th in the Michigan FSAE competition. During his time on FSAE as Team Captain the budget doubled every year allowing the team to grow from less than 5 members to over 25 members. After graduation he became a Ph.D. student at the University of Alabama in the Computer Science Department focusing his research in motorsports on Formula SAE.

His research interests include vehicle simulations for fuel economy, lap performance, and path planning, as well as machine tool path planning and optimization. Cole's qualifying exam research was a literature review on path planning to start the research into real-time optimal path planning algorithms. Cole has written two papers which are on "Optimizing Performance and Fuel Efficiency for a Formula SAE Car" and "Optimizing Gear Ratio Selection for Lap Performance" that both focus on how to improve the performance of a racing vehicle. During his Ph.D. studies the class focus has been on class that would be beneficial in the motorsports and autonomous vehicles. Classes like Autonomous Robotics, Intermediate Dynamics, Nonlinear Controls, High Performance Computing and many others. During the Autonomous Robotics class the students develop an autonomous robot using the TurtleBot3 hardware with ROS. A lidar was utilized with SLAM to search a building and discover new rooms and build a map of the building. During the nonlinear controls class a student based research topic project was given which for Cole was about path trajectory tracking. During the summer of 2019 Cole worked for Hendrick Motorsports helping them develop their Vehicle Simulation program.