Wisconsin Autonomous: White Paper Application for the Indy Autonomous Challenge

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Abstract— **This paper summarizes the progress and future ambitions of Wisconsin Autonomous for registration with the Indy Autonomous Challenge. Wisconsin Autonomous is a student organization at the University of Wisconsin–Madison committed to research and development of autonomous vehicles. Presented first is team history and management, including fundraising capabilities, team structure and testing resources. This is followed by technical development and control architecture for the 2020 EV Grand Prix Autonomous Series competition. An advanced, custom simulation framework was created and leveraged to test vehicle control strategies. Validation was performed on a 1/6th scale test vehicle leading to current integration efforts on a full scale go-kart for the EV Grand Prix competition.**

I. Introduction

Autonomous vehicles have significant potential to drastically improve automotive transportation. Such technology may make driving more accessible, efficient, and safe. For example, vehicles driven by constantly alert sensors and computers could alleviate the number of collisions due to human inattention and error. Similarly, connected vehicles capable of being programmed to monitor an assortment of traffic conditions could reduce overall traffic jams, a welcome relief to the 81 hours per year spent in traffic by the average Los Angeles commuter [1]. With the right implementation efforts, self-driving cars may also be able to alleviate issues such as in-efficient fuel consumption [2] and green-house gas production [3].

A significant challenge to autonomous vehicle development is testing for varied conditions and high-performance driving. While millions of miles have been logged collectively by companies around the world, more validation is needed to prevent accidents until this technology has matured further [4]. Extensive testing will be necessary before self-driving cars can become a reliable part of daily life.

Closed-course competitions such as the 2004/2005 DARPA Grand Challenge have driven rapid advancement in autonomous vehicle technology. Collegiate competitions such as Formula Student Driverless, the EV Grand Prix Autonomous Series and now the Indy Autonomous Challenge encourage similar development efforts in academic programs and emerging professionals. These competitions enable high-performance engineering and testing of algorithms, perception, and control techniques to further progress self-driving car technology in a way that is difficult, expensive, and potentially dangerous to do on public roads. Competitive, collaborative development will contribute greatly to the safe and effective deployment of autonomous vehicles.

At the University of Wisconsin–Madison, Wisconsin Autonomous has the capability and expertise to create and develop autonomous vehicles on closed courses and in virtual environments. With the Wisconsin Automated Vehicle Proving Grounds nearby and a full, physics-based simulation platform in Chrono[5], [6], [7], testing complex software and hardware is easy and reliable.

As a student organization of undergraduate and graduate students with a support system of many faculty advisors, Wisconsin Autonomous is poised to compete at international competitions while developing state-of-the-art algorithms and producing high-caliber talent. Through competitions such as the Indy Autonomous Challenge, Wisconsin Autonomous offers members the opportunity to challenge themselves by designing, testing, and building advanced systems and algorithms for autonomous driving.

II. Team Overview

A. History

University of Wisconsin–Madison has had a rich automotive tradition and has been crowned champion in international competitions 22 times in the last 22 years. These competitions include the SAE Clean Snowmobile Challenge, Baja SAE, Formula SAE, DOE FutureCar Challenge and the DOE FutureTruck Challenge. When not winning, the Wisconsin teams normally record top ten finishes.

Since 2002, the SAE-sponsored competition teams have been housed in the Phil Myers Automotive Center, which was designed and built to accommodate the needs of the engineering automotive teams. This 50,000 square foot facility includes vehicle and welding exhaust removal systems and chassis and engine dynamometers, along with fully stocked

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tool cabinets from Snap-On Tools[8], Milwaukee Tool[9] and C-Tech[10].

In addition to the Phil Myers Automotive Center, the College of Engineering provides a professionally staffed machine shop and prototyping center through Grainger, Inc[11]. Students can mill, lathe, water-jet cut, laser-cut, 3-D print, 3-D scan. After completing specific training levels which include all safety precautions, the students are allowed to reserve and utilize the machines.

B. Faculty Advisor

Dr. Glenn Bower is a Faculty Associate and a Senior Scientist. He has been advising student automotive projects at the University of Wisconsin since 1994. Glenn is responsible for the day to day operations of the Phil Meyer's Automotive laboratory and has numerous industrial contacts/alumni in automotive, recreational and defense vehicle manufacturers.

C. Team Management and Structure

The structure of Wisconsin Autonomous aims to promote interdisciplinary collaboration and group based projects. With six subteams and each subteam consisting upwards of 15 members, collaboration is constant. Many projects require working across subteams so students are exposed to a variety of stages in the engineering design process. This structure is demonstrated in 1. These subteams augment most students' experience in the classroom, where the group mentality is less practiced. This is pivotal for the development of a well-rounded engineer, something Wisconsin Autonomous encourages for all members.

The software portion of our team is broken down into four subteams: perception, state estimation, driving functions and software platforms. These subteams were formed from the steps we identified to be required for a complete control pipeline. The individual efforts made by each subgroup are explained later in the Vehicle and Software Architecture section.

The hardware portion splits into two subteams: vehicle systems and actuation. A driving design characteristic for Wisconsin Autonomous is abstraction between hardware and software. As a result, physical actuation and vehicle design can be developed independently of specific algorithms allowing for less constrained, higher performance development. These two subteams encompass mechanical actuation for steering, braking, and motor control as well as electrical system design and chassis tuning/mounting. Specific progress is described in the Vehicle and Software Architecture section.

The Wisconsin Autonomous business subteam manages internal expenses and fundraising. In addition, a professional website and branding is necessary for coordinating outreach and presenting the organization and greater University of Wisconsin–Madison to the public. For a more in depth description of our business subteam, please refer to the Business section.

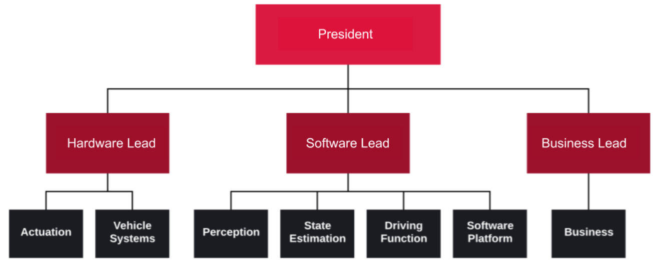

Fig. 1. Team Structure

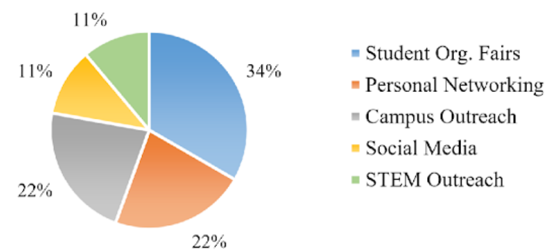

Fig. 2. Recruitment Methods

D. Recruitment and Retention

In order to maintain a large team base, it is necessary for Wisconsin Autonomous to ensure responsible recruitment and retention activities. Traditionally, students have been recruited in multiple ways. Historically, the largest number of students are recruited from outreach events on campus and in the community. Specific student organization recruiting events are also effective at recruiting large numbers of team members. The team has held workshops in the past educating high school students on best coding practices and how to work with various sensors. In an informal capacity, students are recruited by word of mouth and by various social media outlets. A breakdown of current team membership by method of recruitment is displayed in 2.

UW–Madison has always provided a variety of challenging automotive engineering and project planning. This forces students to have strong communication skills and has often required strong team member development at an accelerated pace. Wisconsin Autonomous has developed training methods and projects for their younger members to quickly learn the design, fabrication, integration, and refinement methods commonly implemented in autonomous vehicles. Through continuous improvement techniques, Wisconsin Autonomous manages to teach younger members while integrating them into an otherwise daunting live-action environment.

E. Fundraising and Outreach

In preparation for the Indy Autonomous Challenge, Wisconsin Autonomous has secured funding from multiple revenue streams. Collaboration with industry is key for Wisconsin Autonomous and is a focal point of our support structure.

We are very grateful to our sponsors POLARIS[12], SICK AG[13], SBG SYSTEMS[14] and OSHKOSH CORPORATION[15] for sensors, actuators, parts, and significant financial and knowledgeable support. Their backing and that of our additional sponsors, is greatly appreciated.

The University of Wisconsin–Madison is fortunate to have three different endowments that produce approximately $50,000 of annual revenue, each specifically meant for the automotive projects. Additionally, on an annual basis, the Wisconsin Automotive teams secure over $100,000 of monetary donations in addition to over $250,000 of product donations. UW–Madison is confident that they will competitively fund their Indy Autonomous Challenge team.

F. Testing Facilities

The mission of the Wisconsin AV Proving Grounds (AVPG) is to provide a path to public road evaluation by contributing to the safe and rapid advancement of automated vehicle development and deployment, and providing a full suite of test environments, coupled with research, open data, and stakeholder communication. Two of the AVPG's proving grounds that are available to the Wisconsin Autonomous Team for testing are private, secure facilities as seen in 3:

- MGA Research is located in Burlington, Wisconsin and covers over 400 acres and provides multiple private and secure testing opportunities. This facility was originally the American Motor Corporations (AMC) proving grounds.
- Road America is located in Elkart Lake, Wisconsin with its famous 4.05 mile, 30 foot wide road course utilized by international race series every year. In addition, Road America has 10 plus miles for access roads for autonomous testing.

G. EV Grand Prix and the Indy Autonomous Challenge

The EV Grand Prix Autonomous competition aligns perfectly with Wisconsin Autonomous' goals and ambitions. As the competition requires the use of a kit car, the need for complicated hardware development is minimized. We feel this is ideal for the development of an autonomous vehicle as it allows us to give greater focus to our software and control system architecture, and believe the Indy Autonomous Challenge would further enable this.

The EV Grand Prix provides the perfect first step to transition into the Indy Autonomous Challenge. We plan to take full advantage of the resources and collaboration options provided by the Indy Autonomous Challenge.

Fig. 3. Wisconsin Automated Vehicle Proving Grounds

With the program management, industry support, technical experience, and available resources aforementioned, Wisconsin Autonomous fully intends to be competitive in the Indy Autonomous Challenge.

III. VEHICLE AND SOFTWARE ARCHITECTURE

Preparing for the EV Grand Prix has proved to be a fantastic experience for Wisconsin Autonomous. The hardware portion of our team has been able to focus primarily on vehicle tuning and actuation while our software has been able to focus on simulation and testing of algorithms. This has lead to fluid collaboration and quick progress.

A. Perception

Our perception group is responsible for observing the environment and discerning relevant information from the onboard sensors. The sensors relevant to perception that we have chosen to incorporate on our EV Grand Prix vehicle are a ZED stereo camera[16] and a SICK AG LDMRS LiDAR [17].

For past projects, the perception group has successfully trained a neural network using the YOLOv3[18] structure. Using the depth-sensing ZED stereo camera, a very accurate three dimensional world can be perceived as seen in 4. An additional model was trained to find mini green and red cones for use on our 1/6th scale test vehicle.

For the EV Grand Prix competition, YOLOv3 has proved less useful, as no distinct objects are required to be found. As a result, we have found our LiDAR to be more useful in perceiving the track. This algorithm is visualized in 5, where simulated LiDAR data is used. However, a camera is still useful for tracking other vehicles on the course, which will be equipped with AprilTags[19] fiducial markers.

B. State Estimation

The state estimation group works to accurately localize the vehicle and its surroundings within the physical world. Better known as Simultaneous Localization and Estimation (SLAM), this subteam is responsible for filtering sensor and

Fig. 4. YOLOv3 Model Finding Yellow and Blue Cones using the ZED stereo camera

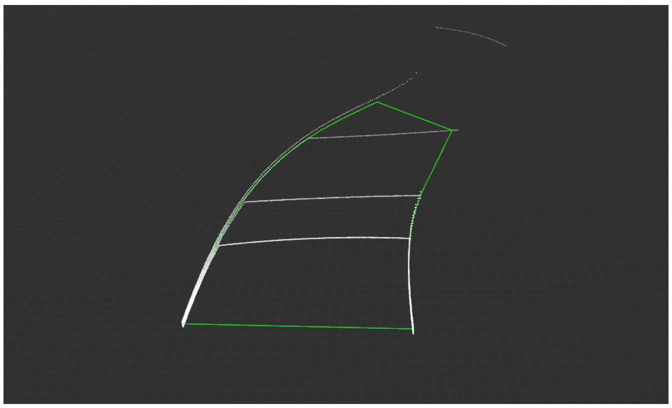

Fig. 5. Track Boundary Detector using simulated LIDAR data

perception data and fusing it with a motion model of the vehicle. Surrounding obstacles are simultaneously localized in both relative and global coordinate spaces to provide a map of the surrounding environment. To test and debug such implementations, simulation has proven to be a pivotal resource. Data can recorded and used in real-time to verify implemented solutions.

Our current solution to the SLAM problem uses a Kalman Filter with other noise-filtering techniques for raw sensor data. We have plans to develop an Extended Kalman Filter for use with a FASTSLAM approach [20]. Depending on performance testing with that algorithm, we are also considering experimentation with GRAPHSLAM [21] and Google Cartographer [22].

C. Driving Functions

For Wisconsin Autonomous, Driving Functions deals with the last portion of the vehicle control pipeline: path planning and path following. Utilizing the maps generated through perception and state estimation, the Driving Functions groups produces high level decisions to pilot the vehicle around obstacles and through the track.

To be as competitive as possible, path generation utilizes complex optimization techniques to minimize time needed to navigate the track. In addition, a PID was implemented, with a variety of heuristics to enhance path following abilities. As other vehicles will be on the track at the same time, an additional obstacle avoidance algorithm was incorporated.

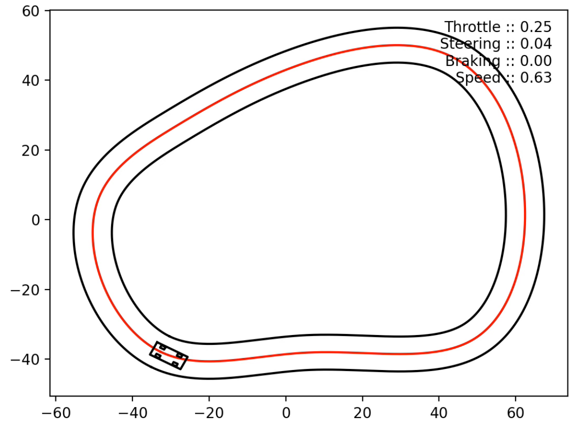

Fig. 6. Visualization of Driving Functions PID Controller

In the pursuit of a robust controls algorithm, the Driving Functions group has also experimented with using reinforcement learning or MPC to pilot the vehicle through the course. For reinforcement learning in particular, simulation is required to thoroughly train the model and successfully determine a suitable policy. In our experiments, a Proximal Policy Optimization[23] based algorithm has been collected and implemented.

For the Driving Functions subteam, it was important that the path generation algorithms could be visualized and tested. This can be seen in 6, where the center line is found between the perceived barriers.

D. Software Platforms

The software stack of the team is, and will be, built off of a modular network of nodes facilitated by ROS (The Robot Operating System). Currently, our use of ROS is motivated by several factors including the availability of drivers for sensors and other hardware, and the separation of concerns that it allows for the necessary functions required in an autonomous vehicle. By breaking our stack into multiple parts, we both increase the maintainability of the individual functions, further the ability for teams to work on pieces more independently, and ensure a higher degree of resilience to faults at any point in the pipeline.

In addition, the Software Platforms subteams work on the vehicle to develop essential electrical-based components. For example, a remote stop was designed by the Software Platforms group to be integrated into the shut-down circuit on the vehicle. Furthermore, assisting with CAN messages for actuator control has been a primary focus for much of this team.

E. Vehicle Systems

Our vehicle systems team is in charge of tuning the vehicle chassis and performance characteristics as well as fabricating mounting components. After completing the kit build for the EV Grand Prix, this subteam has been focused on testing vehicle handling performance. With some vehicle parameters and properties relevant to the software team and its simulation platform, sophisticated vehicle models were designed and evaluated by our control algorithms.

As the EV Grand Prix Autonomous challenge requires teams to incorporate a variety of sensors and computation hardware into their kit builds, the Vehicle Systems subteam has helped develop mounts for these components. A compact and lightweight mounting platform for the LiDAR and stereo camera was designed and machined. Moreover, a secure structure was developed to secure our GPS and IMU sensor and the processing units used. The subteam is also working to design and produce supportive mounts for our power steering and brake-by-wire units.

F. Actuation

With the fine degree of control desired for autonomous driving, robust and high-performance actuation is a necessity. Due to the generosity of our sponsors, all of our actuation has been supplied by different companies. This has allowed us to focus on generating well designed mounts and control software for these actuators.

To both steer and brake our vehicle, we are currently using modules generously provided to us by POLARIS. Both the power steering and brake-by-wire units communicate to our computing system over CANbus. This has allowed us to limit the number of processors we have on board, reducing latency between systems.

IV. TESTING PLATFORMS

A suitable and comprehensive simulation platform is necessary to successfully develop an autonomous vehicle. Sending out an unproven vehicle onto roads can lead to unexpected results and possibly dangerous consequences. With a simulation platform, realistic and unrealistic scenarios can be tested to observe how the control stack will respond. In this section, a custom, high fidelity, physics based simulation platform is presented.

Additionally, to further solidify and verify the algorithms we implement, it is important multiple testing frameworks are available. As a result, we purchased a 1/6th scale RC car and retrofitted it with a microprocessor to actuate the steering and throttle without the need for a remote, as seen in 7. This is again another way to test our code, and we will describe this use case in this section.

A. Chrono

The basis of an autonomous vehicle simulation framework is project Chrono. Chrono is a simulation platform created by Professor Tasora in 1997 and has since been used and developed by the Simulation Based Engineering Lab at the University of Wisconsin-Madison. This is an open-source C++ library with the goal of supporting simulation in numerous engineering applications including robotics, granular materials, and vehicle dynamics especially when massive, scaling systems are required [5], [6], [7]. To address the need for virtual autonomous vehicle testing, Chrono has been, and will continue to be, augmented to provide sensing capabilities, dispersed simulation of autonomous algorithms which will protect proprietary aspects of vehicle development, and expansive virtual world support.

Because autonomous vehicles make decisions largely off of sensor feedback from the world around the vehicle, utilizing virtual sensors is a key component of any autonomous vehicle simulation platform. Sensing in physical systems can be difficult and is a source of error when calculating path planning and obstacle detection. This is why the sensing capability of Chrono is of utmost importance. It is vital the virtual sensors provide a realistic image of the surroundings back to the vehicle and can replicate noise and error observed by their physical counterparts. Some current robotics simulation platforms incorporate sensor data simulation such as Gazebo and V-REP, but these simplify the noise models by assuming a Gaussian distribution. While this represents uncertainty, many sensors are dependent on environmental conditions such as rain, fog, or snow which is vital in autonomous vehicle simulations[24].

The sensor module in Chrono is responsible for generating and recording data representing the data accumulated by various sensors. Sensors currently available in simulation include a camera, LiDAR, GPS and IMU.

B. Generic Interface Control

One of Chrono's main goal is to provide a suitable testing environment for autonomous algorithms, from car-following schemes to complete control pipelines. Each control algorithm is independent of Chrono, allowing the programmer to determine the action of the agent. In this section, the contributions provided by Wisconsin Autonomous for the Chrono framework are described.

One possible use case for Chrono is to study highway dynamics, where flow rates and/or traffic shock waves are analyzed. In this scenario, the brain is not necessarily being studied, so the processing of sophisticated sensor data is not important. Instead, the simulation environment can be leveraged to give exact positions and velocities directly to the agent. Such an approach is realistic when the behavior of a group of agents is of interest instead of that of a single vehicle. In the platoon example, the repercussions of a single vehicle lane change in a crowded highway scenario of multiple autonomous vehicles can be analyzed.

For other users, the autonomous strategy is of particular interest. In this case, the importance of sensor data increases. LiDAR, camera, GPS and IMU is analyzed and a vehicle control strategy is utilized to pilot the vehicle through the simulated environment. In this case, exact positions of the world are ignored, and the control stacks integrity is upheld. These simulations are unfortunately limited in their scope, as in order to keep hardware-in-the-loop, cuda enabled GPU's are required. [25].

In another scenario, it may be worthwhile to control the simulated vehicle through keyboard or steering wheel inputs.

This wide breadth of vehicle control types necessitates a flexible method for changing and implementing vehicle brains.

For Chrono to be a viable simulation framework for testing autonomous algorithms, it is important that going from simulation to reality is seamless. For situations where the developed pipeline is meant to be retrofitted on a real-life vehicle, this feature is imperative.

To this end, our contribution to the Chrono framework is an interface that has been developed which promotes a "drag-and-drop" style transition. Using TCP as the means of communication, Chrono can send information about the simulated environment to a receiver outside individual simulation. In this case, a controller could be used in a framework similar to Robot Operating System (ROS), of which analyzes the communicated information. With the use of this interface, a complete control pipeline independent of the Chrono structure can be run with inputs replicating those from reality, such as sensor data or V2X communication. With controls algorithms not necessarily written in Chrono's native C++, it is also important this interface provides a way for languages such as Python and MATLAB to interact with the simulation (the latter not using TCP, but instead MATLAB's own C++ interface).

C. 1/6th Scale Vehicle

An autonomous 1/6th scale vehicle, was created as another test bed for verifying our implemented algorithms. The scale vehicle, along with its computational hardware, can be seen in 7.

While simulation can provide highly realistic scenarios, having a physical counterpart was pivotal to the success of the software subteam. To verify functionality and accuracy of sensors to be used on the full scale vehicle, the RC car allowed us to practice using the sensors on a moving vehicle. In addition, it gave us practical experience converting the simulated control stack to a physical control pipeline.

Furthermore, the main advantage of this scale vehicle was to provide the software team some physical test bed to verify algorithms whilst the full scale car was being built. This provided a verification of simulated scenarios and another way to ensure our code was robust. Even when the full scale vehicle became ready to use, it was easy and reliable to test new algorithms inside using the scale vehicle.

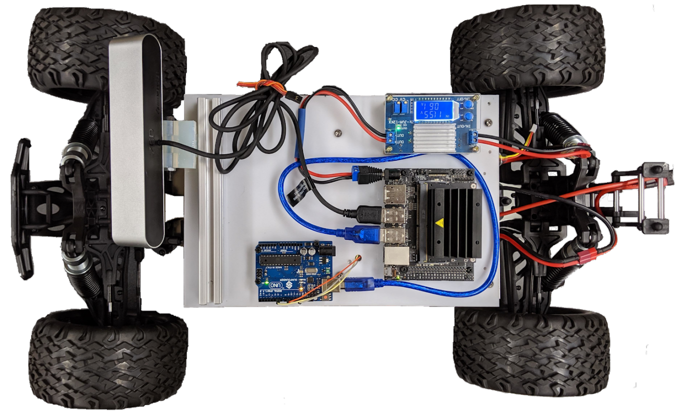

Fig. 7. 1/6th Scale Test Vehicle

D. Results

For Wisconsin Autonomous, utilizing a simulation environment has proven extremely powerful. When a simulation environment is used, it is important that world be as similar as possible to the physical counterpart. For Chrono, high fidelity vehicle models can be generated and accurate worlds can be visualized using highly transferable sensor data. Without a vehicle to physically test, the simulation environment has enabled members to make progress off-site while still being able to verify their algorithms.

In the case of the scale vehicle, in order to replicate these simulated scenarios, we decided that it was best to create a simulation environment that looked like what the scale vehicle would see. As a result, we purchased small cones. We then generated a 3D model of these cones and put these in simulation. This allowed us to then verify control strategies, SLAM techniques and perception based algorithms. We even experimented with using simulated camera data to train a YOLOv3 model. An example of this environment and its physical counterpart can be seen in 8.

Additionally, a Chrono model of the RC car was created to ensure the "drag-and-drop" was as fluid and accurate as possible.

In preparation for the EV Grand Prix competition, a duplicate course of what would be seen on track was created in simulation. This can be seen in 9.

V. Conclusions and Future Work

This paper introduced the student organization Wisconsin Autonomous and its work thus far. The development of an autonomous vehicle has not proved easy, but with our

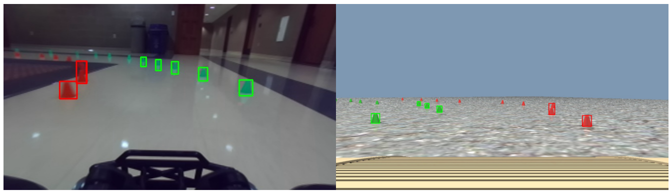

Fig. 8. YOLOv3 Model Used in Reality and Simulation

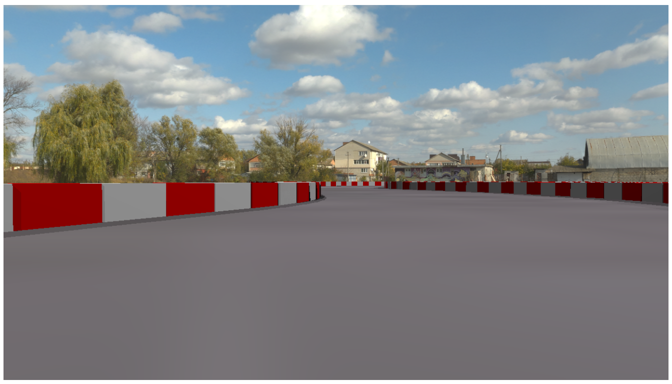

Fig. 9. Realistic EV Grand Prix Simulation Environment

contribution to the Chrono framework, the utilization of a 1/6th scale vehicle and the development of our kit car, progress has been astounding.

In pursuit of the EV Grand Prix Autonomous Series, Wisconsin Autonomous has found creative solutions to difficult problems. With its robust team structure, interdisciplinary work is seamless and collaboration is encouraged. Financial support, component sourcing, and professional expertise for our vehicle and control stack has been made possible through help from our variety of generous sponsors.

The Indy Autonomous Challenge will provide a new challenge for members of Wisconsin Autonomous. With a fantastic team foundation that has been facilitated by development for the EV Grand Prix competition, we are prepared to perform up-to-date research and make significant contributions to the autonomous vehicle industry.

Future work will focus on more complicated control strategies, such as using reinforcement learning to pilot our real vehicle through the barrier course. Similarly, a more powerful LiDAR sensor may be purchased, allowing our team to more accurately perceive the world around it.

In only its second year, Wisconsin Autonomous has proven it is capable of developing successful control strategies and a working racing vehicle. With the ultimate goal of contributing to the automotive and self-driving car industries, Wisconsin Autonomous aims to make a lasting impact with the Indy Autonomous Challenge.

ACKNOWLEDGMENT

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