Pathfinder Design Report

Ohio University PAVE Team

2019/5/15

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I hereby certify that the design and development of the vehicle Pathfinder, described in this report is significant and equivalent to what might be awarded credit in a senior design course. This is prepared by the student team under my guidance.

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1. TITLE PAGE

2. DESIGN PROCESS, TEAM IDENTIFICATION AND TEAM ORGANIZATION

Introduction

The Professional Autonomous Vehicle Engineering (PAVE) team from Ohio University (OU) has designed and developed the autonomous ground vehicle, dubbed *Pathfinder*, to join the 27th Annual Intelligent Ground Vehicle Competition (IGVC). Our team members include undergraduate and graduate students in the School of Electrical Engineering and Computer Science (EECS), Mechanical Engineering (ME) Department and other departments in the Russ College of Engineering and Technology of OU, under the guidance of Professor J. Jim Zhu and with consultations to other faculty and technical staff. The Pathfinder is a modified sub-scale toy car equipped with a novel autonomous control system comprising a patent-pending motion control sub-system for autonomous driving and steering, and a novel cognitive control system comprising a novel 3D visual perception sub-system, a cognitive state machine and a patent-pending guidance sub-system for obstacle avoidance and trajectory planning. Last year, we entered IGVC for the first time. However, due to the limited development time and a faulty component at the competition, we were not qualified for the Auto Nav Competition. Based on last year's design report [1], this report details the progress in this year's design process, technical approach, test results to date, and plan for the remaining days before the competition.

Organization

Figure 1 shows the team structure for the engineering process, where the System Engineering Group (SEG) oversees the managerial and technical development of the Pathfinder. There are six task-based engineering groups working on the various technical aspects delineated later in this report. This year, 24 PAVE members actively contributed to the development, and their names, email, academic department and class, amd engineering roles are shown in Table 1.

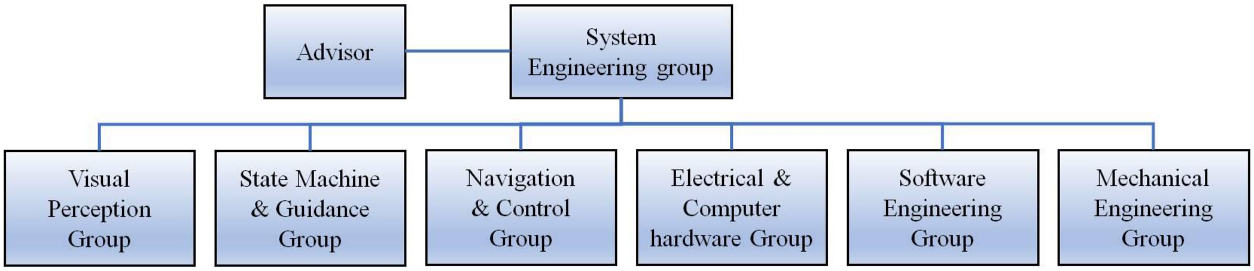


Figure 1. Organization Structure.

Table 1. Team Members.

Advisor: Dr. J. Jim Zhu							
Name	**Level**	**Major**	**Task**	**Name**	**Level**	**Major**	**Task**
Yuanyan (Amy) Chen	G-PhD	EE	SE/C	Tessa Berger	UG-Se	ME	M
Letian Lin	G-PhD	EE	SE/G/EO	Brandon Cote	UG-Se	ME	M
Yang Liu	G-MS	EE	SE/N	Garret Knapik	UG-Se	ME	M
Miguel Sempertegui	G-PhD	EE	M	Stefan Lombard	UG-Se	ME	M
Stuart Randle	G-MS	EE	CE/S	Keith Sebald	UG-Se	CS	SW/EO
Robin Kelby	G-MS	CS	SW	Shipeng Yang	UG-Se	CS	SW

David Masters	G-MS	CS	SW	Bohong Li	UG-Se	CS	SW
Jacob English	G-MS	CS	SW	Jordan Ward	UG-Se	CS	SW
Leyder Nicholas	G-MS	CS	SW	Jeremy Beauchamp	UG-Se	CS	SW
Kaiyo Mao	UG-Jr	EE	EP/EO	Trenton Davis	UG-Se	CS	SW/EO
Zachary Thompson	UG-Jr	EE	EP	Xudong Yuan	UG-Se	CS	SW
Dylan Wright	UG-Jr	CS	SW/M	Zhaojie Chen	UG-Se	CS	SW

* **SE**: System engineering, **C**: Control, **G**: Guidance, **S**: Safety, **N**: Navigation, **M**: Mechanical, **EP**: Electrical and Power, **SW**: Software, **CE**: Computer engineering, **EO:** PAVE Executive Officer

Design Assumptions and Design Process

To ensure the ultimate success in such a multi-disciplinary engineering project, we followed strictly the good practices in system engineering for management, design, and testing. Under the leadership of our SEG, we started by studying the competition rules carefully, and turning them into design assumptions and requirements. Then through brainstorming, initial system Concept of Operation (ConOp) was developed for the vehicle sub-system as shown in Figure 2, the software strategy for the autonomous control sub-system comprising a motion control sub-system and a cognitive control sub-system as shown in Figure 3, and the electronic and power sub-system as shown in Figure 4. Based on these design concepts, optimal technical approaches were selected through tradeoffs, and tasks were broken down and delegated to each task group. Weekly project management meetings were conducted to assess progress, issues and risks. Important engineering and purchasing decisions were made at these meetings and approved by the advisor.

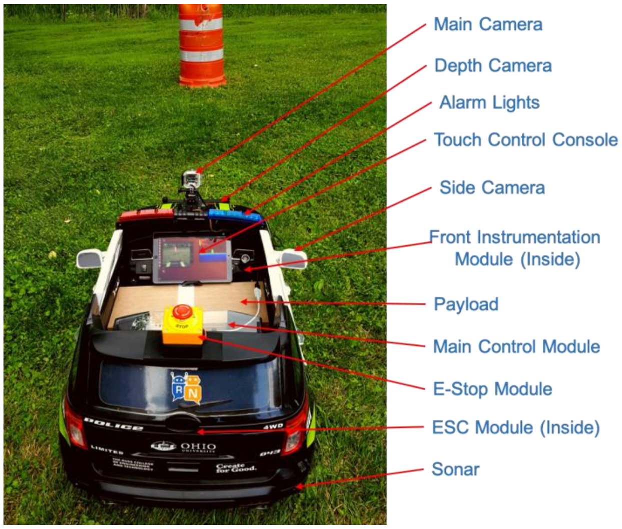


Figure 2. Vehicle System.

In addition to our SEG guided design activities, the visual perception software module and the cognitive state machine software module were developed by two CS senior design teams (4 members each), and the suspension system was developed by a ME senior design team (4 members) in their year-long capstone design classes following the industrial design process. Four CS graduate students in our team who were taking a graduate course on Pattern Recognition designed part of the line and pothole detection software as their course projects.

We choose the toy car for IGVC in part because of its realism to personal transportation vehicles, but also because car-like ground vehicle configurations are more suitable for high-speed operation. Table 2 summarizes the modifications to the original vehicle made last year, and the changes made this year.

3. INNOVATIONS

The design of Pathfinder includes the following innovations

- Magnetic dampers in the suspension system
- A novel bio-psychically inspired cognitive autonomous control architecture [8] [9]
- Optical flow for ground velocity measurement
- 3D visual perception for obstacle detection

- Cognitive state machine for decision making
- Patent pending line-of-sight pure pursuit guidance trajectory generator [2] [7] and a switching control based path planner [4]
- Patent pending 3DOF Trajectory Linearization Controller for simultaneous and precise drive and steering control [3] [5] [6]

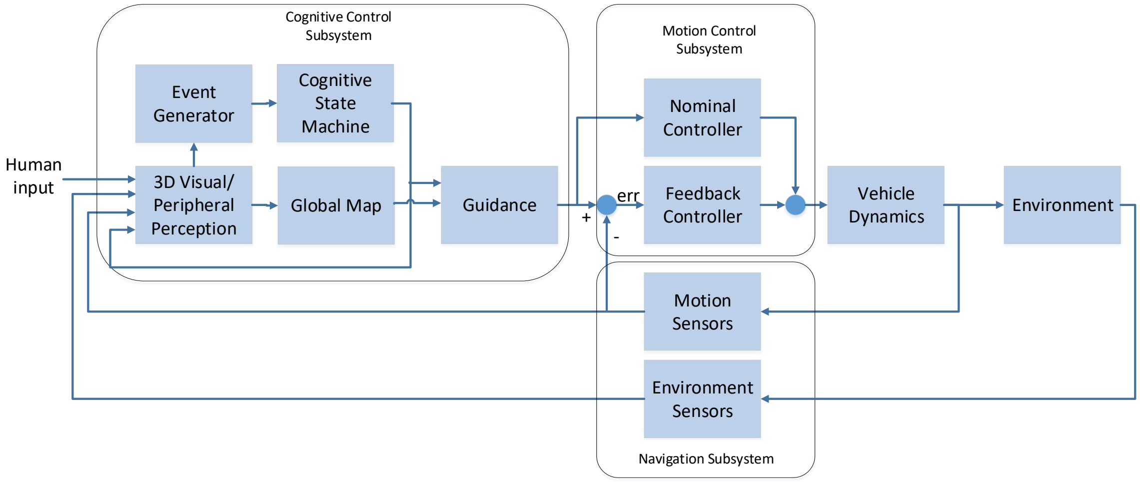
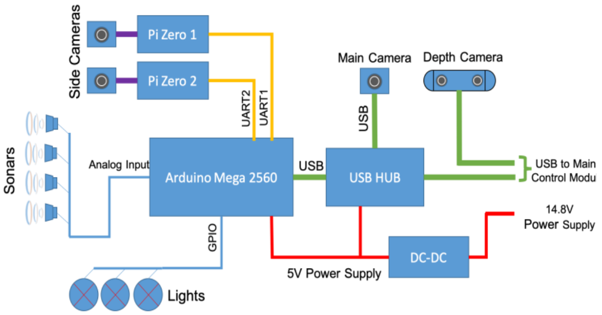
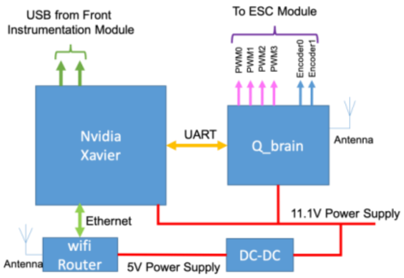


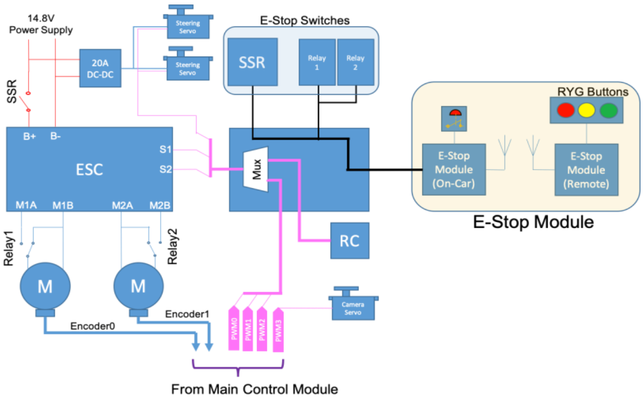
Figure 3. Autonomous Control System.



(a) Front instrumentation module



(b) Main control module



(c) ESC & E-Stop module

Figure 4. Electronic and Power System.

Table 2. List of Improvements.

Components	Stock Vehicle	Pathfinder 2018	Pathfinder 2019
Mechanical and Body			
Steering	DC motor with left/right control	Dual servo control.	High Torque servos.
Wheels	Rigid plastic wheels and tires	Steel wheel with pneumatic tires	---
Gearboxes	Low RPM, high torque	High RPM, lower torque	---
Motor	Low RPM, low power	High RPM, low power	Higher RPM, high power
Frame	Mostly plastic with steel subframe	Strengthen frame with room for payload.	---
Interior	Child seat and toy steering wheel	Removed steering wheel and seat to make room for electronic components.	Separate compartments for computational module and footwell protection
Suspension	Short stroke springs for rear and front suspension.	Stiffer springs for rear suspension with magnetic damping	---
Electrical/Power			
Emergency stop	---	Faulty implementation, unable to qualify for competition	Improved and verified
ESC board	---	Low power ESC	Higher power ESC.
RC override	Limited ON/OFF control	---	Full RC/Auto switching
Electronic Hardware			
Cameras	---	One camera (bumper mounted).	One main camera (roof mounted) and two side cameras (in wing mirrors).
Depth measurement	---	2D Lidar	Intel D435i depth camera
Motion control computer	---	Quanser HiQ	Quanser Q-Brain
Cognitive Control Computer	---	Nvidia TX2	Nvidia AGX
Dashboard Display	---	---	Dashboard mounted display.
GNSS	---	Simple GPS receiver	High performance 4-constellation GNSS module.
Software			
Motion Control	---	TLC tracking controller for forward driving only	Improved TLC tracking controller with reverse
Guidance	---	Incomplete	Completed LOS guidance
Decision Making	---	Ad hoc state machine, incomplete	Completed general purpose state machine
Environment Perception	---	Ad hoc vision and Lidar processing, incomplete	Completed modular 3D environment perception

4. MECHANICAL DESIGN

Overview

The overall design of Pathfinder aims to accurately replicate the real-life conditions and response of an everyday personal transportation vehicle but in a smaller scale whilst including all the necessary technological components of an autonomous ground vehicle platform. The mechanical design for Pathfinder consists of a main body, modified from four-wheel toddler sit-in toy vehicle, that houses several electronics compartments, sensors, cameras, and a main computational module.

Chassis

The vehicle has been considerably modified from its original state to improve its performance and control precision. The main body, as shown in Figure 2, is comprised of single piece of a semi-rigid polymer that is sufficiently sound to provide structural stability to the vehicle. Because of the payload dimensions, the vehicle frame had to be modified and reinforced to accommodate it, see Figure 5.

Figure 5. Payload Compartment with Payload in.

Drive System

The driving mechanism that was installed originally on the vehicle lacked the speed, power and traction needed to complete the required task. Thus, the four plastic tires were replaced by pneumatic tires that provide additional traction and a certain degree of suspension. DC motor with a higher RPM and power rating than the factory ones were placed as the main drive mechanism so to increase the maximum speed and payload capability of the vehicle.

Figure 6. Drive mechanism with larger motor (gearbox + motor).

Steering System

The original steering mechanism employed a DC motor, which did not provide enough control authority over the steering angle of the front wheels. It was replaced last year by a custom mechanism that uses two digital high-torque servo motors that provide an adequate level of control for the steering mechanism. However, those servos were overloaded and permanently damaged in a recent test, so two larger servos will be installed to allow for more fail-safe operation.

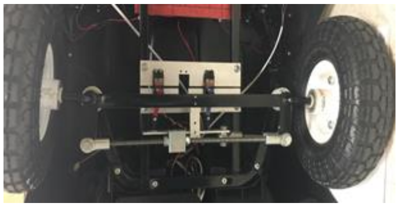
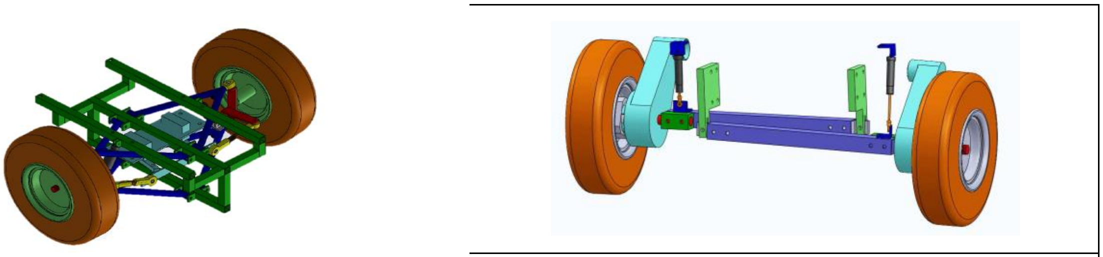


Figure 7. Steering Mechanism.

Suspension System

The original front and rear springs were replaced with new ones with a proper stiffness of 21 lb/in. Additionally, two magnetic dampers were implemented using permanent magnets that are fixed on the chassis and copper tubing connected to the real axle, as shown in Figure 8, to generate a viscous friction force by means of the induced eddy current to damp the vibrations. The viscous friction between the steering shaft and its bushing bearings were relied on for damping. Together with the new pneumatic tires, initial testing showed much improved and acceptable performance. Since last year's competition the front and rear suspensions have gone through a redesign process.

In order to further reduce vehicle vibration, which had significant adverse effects on the image processing, this year the front and rear suspensions have been redesigned as shown in Figure 8. The front suspension is comprised of a double a-arm to give individual suspension to the front tires and increase stability of the vehicle. This new design is in the early stages of implementation. The rear suspension is comprised of a double-I beam that provides a larger stroke. However, field tests revealed an undesired deflection when load is applied, and it is currently under revision.



(a) Front suspension

(b) Rear suspension

Figure 8. Suspension design.

Electronic Housing

In order to protect and organize the main motion control computer and the cognitive control computer, a compartment was fabricated using 3D printed parts and plexiglass. It provides housing for the two computational units and cover the main drive unit in the rear axle.

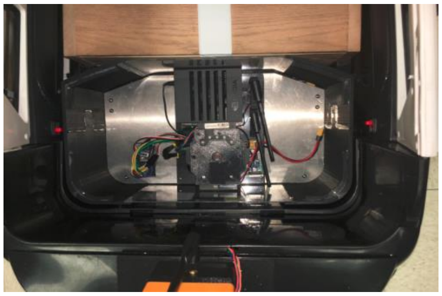


Figure 9. Computational Module.

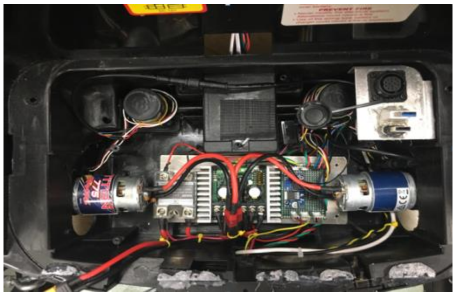
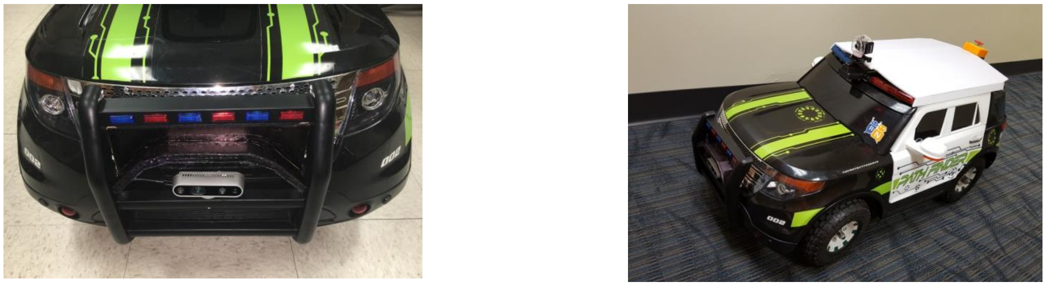


Figure 10. ESC compartment.

Weather Proofing

The overall design of Pathfinder considers the proper placement of electronic devices and mechanical components for weather protection. In general, all the critical elements are stored in such a way that precipitation and dust do not come in contact with them except on exceptional cases. For more extreme conditions, a front depth camera rain cover and a cabin rain cover made of water repellent foam-core boards can be attached to the vehicle quickly.



(a) Camera rain cover

(b) Cabin rain cover

Figure 11. Rain cover.

5. ELECTRONIC AND POWER DESIGN

Overview

This year, the electrical system adopts a modular design with four modules. They are Main Control Module, Front Instrumentation Module, ESC Module and E-stop Module. All the modules are connected by high quality connectors.

Main Control Module (CPU)

Figure 12. Main Control Module.

The Main Control Module, as shown in Figure 12, is the brain of the autonomous vehicle. It is composed of Nvidia AGX and Q_Brain. Nvidia AGX is in charge of Environment recognition, Path Planning and State Machine. Finally, it will generate an executable trajectory for the motion control unit. Q_Brain is the motion control unit, which employs the TLC control algorithm to track the trajectory with agility and precision.

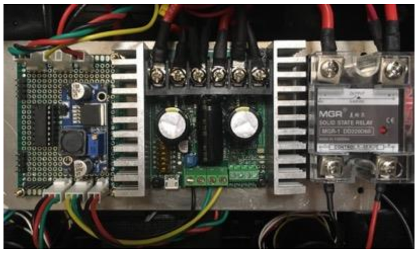


Figure 13. ESC Module.

Electronic Speed Control (ESC) Module

The ESC Module drives the motors. It is made up of drivetrain, the Control Signal Multiplexer System and the Emergency Stop Switching System, as shown in Figure 13. This year, we upgraded the power of the drive motors. By using Traxxas Titan 775 to replace Traxxas Titan 550. The power increased by 50%. Based on this improvement, the acceleration and deceleration performance and ramp climbing performance increased by 50%. We kept the max speed at 2.2m/s to match the max speed requirement of this competition.

E-stop Module

E-stop Module includes on-car emergency stop button and remote stop controller, as shown in Figure 14. This module will generate the emergency control signal for the Emergency Stop Switching System that will cut off the power supply and apply regenerative braking the motors in emergency situations.

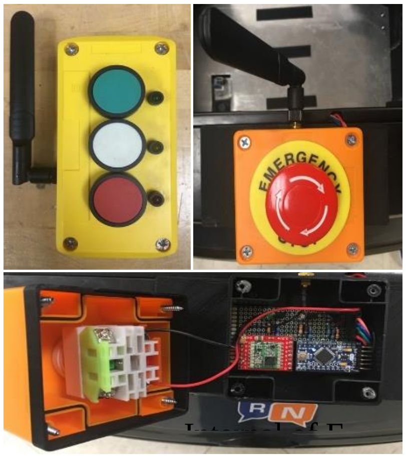


Figure 14. ESC Module.

Front Instrumentation Module (Sensor Integration)

The Front Instrumentation Module houses sensor data acquisition and pre-processing components. It collects the information from the main RGB camera (Figure 15a), depth camera (Figure 15b), sonars (Figure 15c) and side cameras (Figure 15d, e, f). The RGB camera and depth camera data are passed to Main Control Module directly, others are pre-processed by the Front Instrumentation Module microcontroller and then passed to Main Control Module.

(a) Front Camera (b) Depth Camera (c) Sonar

(d) Side Camera (e) Side Camera (inside) (f) Side Camera View

Figure 15. Environmental Sensors.

Cost breakdown

The main costs of this autonomous car are Quanser Q_brain and Nvidia AGX. With educational discount, Quanser Q_brain cost $4700 and Nvidia AGX cost $1200. For high value sensors, depth camera cost $200, GPS cost $200. In addition, all the electronic and mechanical miscellaneous items cost around $3000. In total, the value of the car about $9000.

Power distribution system

The power distribution system was designed to separate the power supplies of drivetrain and instrumentation system. For instrumentation, the Q_brain and Nvidia AGX consume the most power. They roughly need 8A for operation. In the drivetrain system, the driving motors and steering servos are the main power consuming devices. On level ground, they need about 3.3A to run at 2.5m/s. For 15% ramp condition, their current drain is 8.3A at 2.5m/s approximately.

Based on these data, the predicted battery performance is shown in Table 3

Table 3. Battery Life Calculation.

Power Source	Specification	Charge Rate Charge/Discharge	Power Consumption				Battery Life
			Normal	Duty Cycle	Peak	Duty Cycle	
Instrumentation Battery	5.5Ah/11.1V	5C/35C	80W	95%	107W	5%	45min
Drivetrain Battery	4Ah/14.8V	5C/30C	50W	90%	122.8W	10%	55min

6. SOFTWARE STRATEGY AND MAPPING TECHNIQUES

Overview

This section describes our software strategy for line following, obstacle detection, high-level decision making, mapping, vehicle guidance and control.

Vision System

Vision is an integral portion of an autonomous vehicle for environmental detection. According to the competition rules, the vehicle is required to stay in the course and have the ability to avoid the obstacles. The vision system is designed to be modular in nature and can be integrated with the other subsystems. The inputs for the vision system are the color image obtained from the front color camera and the depth image obtained from the depth camera. By using the color image, the vision system is able to detect the track lines and the potholes in the course. The flow chart of line and pothole detection is shown in Figure 17.

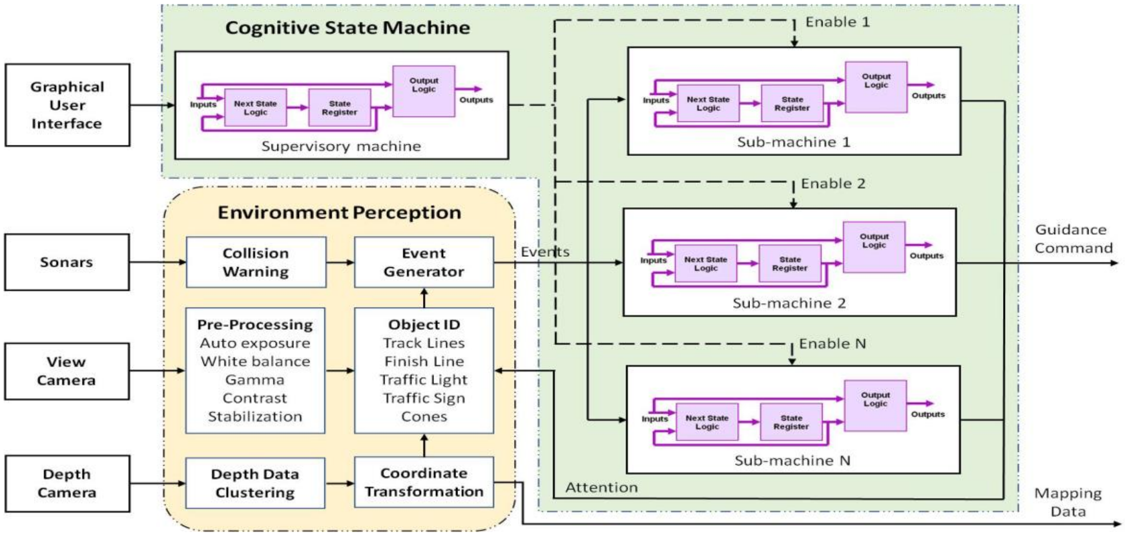


Figure 16. Perception-Decision System.

In Figure 18, the white track line in the camera view is indicated by the green dots and their fitted curve which is represented by the blue line. The two magenta lines bound the region of interest (ROI). The magenta square is used for white balance. The processed image in the ROI shows the resulting binary image after thresholding. The green dots are determined by scanning at different lookout ranges for the clustered white pixels from a dynamic center of the road to the boundary of the image. In Figure 19, the color image shows the camera view for a white pothole in the course. The resulting binary image after thresholding is shown in the processed image in ROI. By applying the clustering algorithm to the processed image, the pothole is recognized.

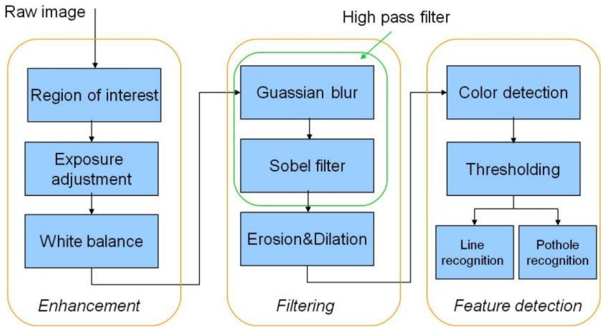


Figure 17. Color Image Processing Strategy.

The obstacles are detected by using the depth camera together with the color image. By applying the clustering algorithm to the depth image, the potential positions of the obstacles are located. In case of false positive, the centers of potential obstacles are mapped to the color camera frame. By using color detection in the neighborhoods of these mapped centers, the real obstacles can be confirmed.

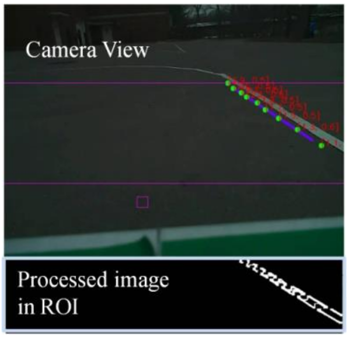


Figure 18. Line Detection.

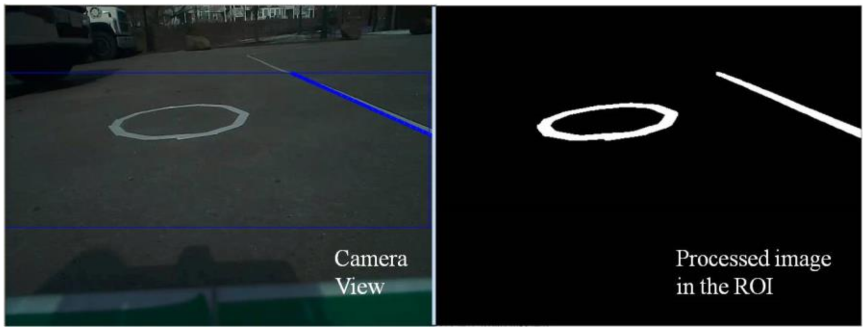
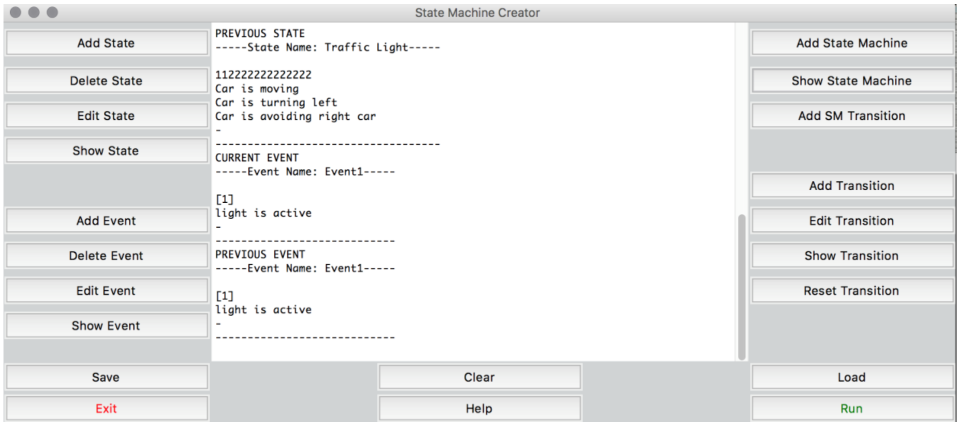


Figure 19. Pothole Detection.

Figure 20. Screen Capture of Obstacle Detection.

Cognitive State Machine

The event-driven cognitive state machine, which is a Mealy machine, conducts the high-level decision-making. The command from the graphical user interface (GUI) and the events generated by the environment perception system serve as the input to the cognitive state machine. The events together with the current state determine the state transition. The output logic sets the appropriate output commands according to the current state and input. The display of the GUI is shown in Figure 21. According the competition requirement, a state high-level machine is built as shown by the bubble chart in Figure 22.



```
PREVIOUS STATE
-----State Name: Traffic Light-----

112222222222222
Car is moving
Car is turning left
Car is avoiding right car
-
-----------------------------------
CURRENT EVENT
-----Event Name: Event1-----

[1]
light is active
-
----------------------------
PREVIOUS EVENT
-----Event Name: Event1-----

[1]
light is active
-
----------------------------
```

Figure 21. State Machine GUI.

Mapping

The mapping system is responsible for building a local map in the body frame and a global map in the world frame is shown in Figure 23. Specifically, mapping is conducted in the following steps:

Retrieve the local map from the global map according to the position of the car, if it is available, then convert the local map to body frame, at which point a nominal path is planned.

1. The road line position in the color camera frame and the obstacle position in the depth camera frame are mapped to the body frame and represented by discrete points. Then, these points are converted to the local map.
2. By using the old data in the local map, a Kalman filter based smoothing algorithm is used to alleviate the noise in the sensed data of the line points in the local map.
3. By using polynomial spline fitting, the road lines are represented by a vector graphic in the local map.

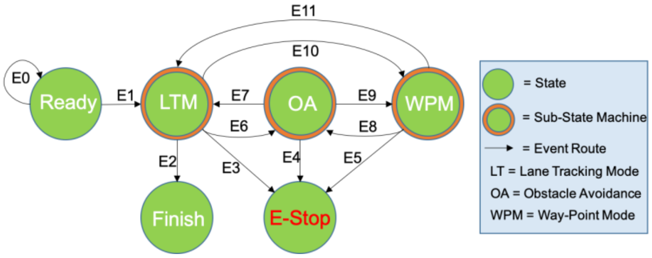
4. The local map is used to update the global map in the world frame.

Figure 24 shows a test track and the corresponding global map built by our mapping technique. This global map can help to speed up the vehicle in the course.

Guidance

The guidance system is responsible for generating a kinematically and dynamically feasible, collision free command trajectory that leads the vehicle to the destination. In guidance design for lane following, the line-of-sight (LOS) pure pursuit guidance (PPG) is used. After the local map is retrieved from the global map, LOS PPG design consists of the following steps: (1) The longitudinal speed u is selected according to the curvature of the reference path, the infrastructure speed limit, the lookahead certainty and the dynamic constraint. (2) The lookout distance l is selected according to the reference path and u. (3) A virtual target is selected on the reference path at a distance l ahead of the vehicle. (4) Design a guidance law to steer the vehicle to align its velocity vector with the LOS. The guidance system diagram is shown in Figure 23.

If the global map is known in advance, a nominal path can be generated for a relatively long distance and LOS PPG can be conducted on it directly. The nominal path will be modified when there is significant change in the environment ahead. If the global map is unknown, LOS PPG can still guide the vehicle traveling forward. In such case, the global map will be built as the vehicle explores the environment.



Events	Description
E0	No Start Command
E1	Start
E2	Finish Line Arrived
E3	Emergency Stop in Lane Tracking
E4	Emergency Stop in Obstacles Avoidance
E5	Emergency Stop in Way-Point Mode
E6	Obstacle Detected in Lane Tracking
E7	Obstacle Passed in Lane Tracking
E8	Obstacle Detected in Way-Point Mode
E9	Obstacle Passed in Way-Point Mode
E10	Way-Point Start Arrived
E11	Way-Point End Arrived

Figure 22. State Transition Diagram.

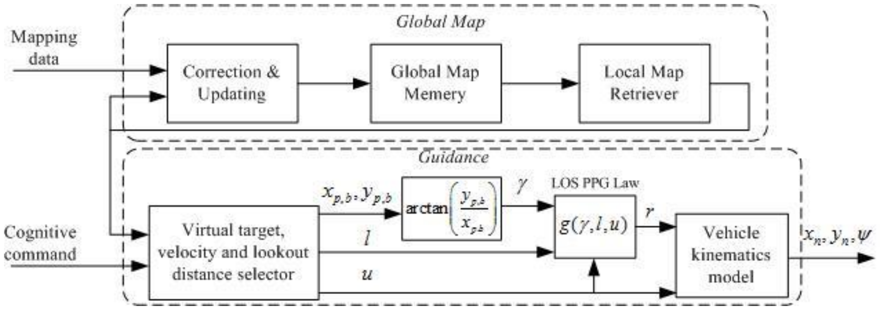


Figure 23. Global Map and Guidance.

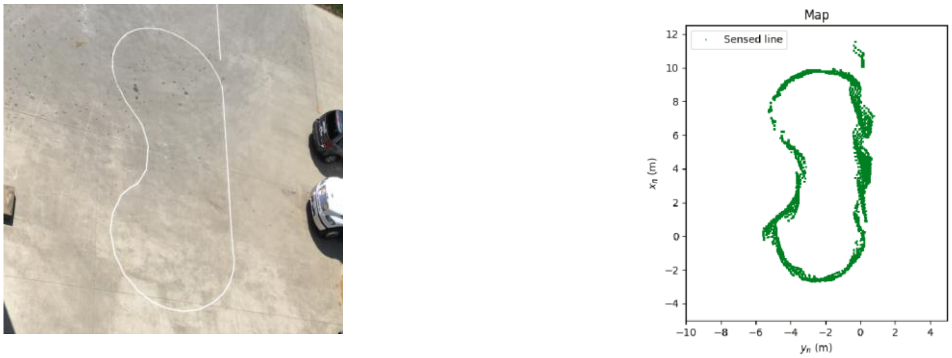


Figure 24. Track Line Global Mapping.

In order to avoid obstacles in the course, the system first determines which side of the obstacle has a wider passage under the constraint of the road. Then, a reference path is designed by using polynomial splines to avoid the obstacles and maintain smoothness of the path. A collision-free nominal trajectory can then be generated by using LOS PPG. A simulation result for obstacle avoidance under LOS PPG in the lane following is shown in Figure 26. Under the assumption that the environment is passible, if the environment is tight, the waypoints that will lead the vehicle traveling forward are selected. Then, the nominal path can be generated between the waypoints by using polynomial spline fitting. Thus, the vehicle can be guided out of the tight part under LOS PPG along the nominal path. For open area guidance, the nominal path can be directly planned to the GPS waypoint. If there are obstacles in the way, polynomial splines are used to avoid them.

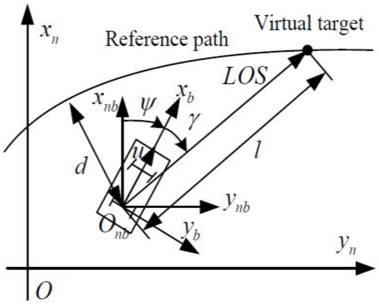


Figure 25. LOS PPG for Autonomous Vehicle.

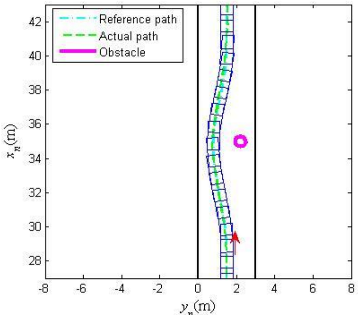


Figure 26. Obstacle Avoidance by Using LOS PPG.

Navigation and GPS Localization

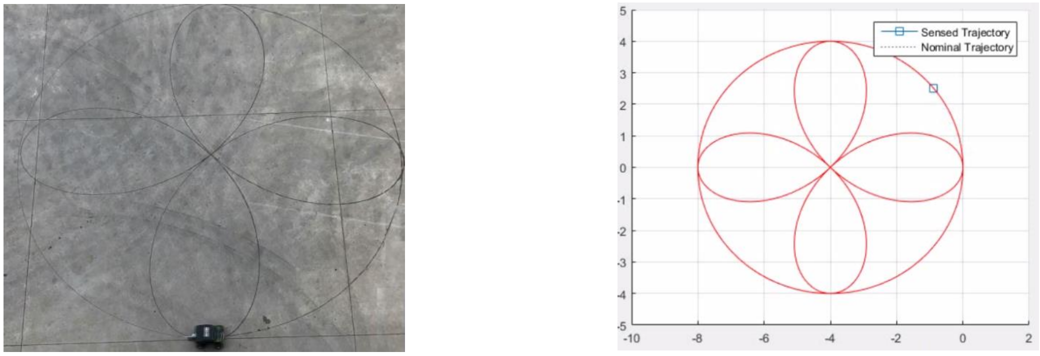
The Motion Sensor System includes GPS/INS and motor shafe encoder. In practice, the onboard inertial sensors, like gyroscopes and accelerometers will have some bias. If these signals are used directly to calculate the orientation and position by integration, the results would drift because of the bias. Comparing to inertial sensors, GPS is much more accurate over time, but the data update frequency is lower than inertial sensors. The quadrature motor shaft encoder can be erroneous when vehicle is in dynamic motion due to wheel slipping and skidding, but it provides relatively accurate velocity data when the vehicle is running at constant velocity. Accordingly, a bias removal function is applied to the inertial sensors, and a Kalman filter algorithm is employed for sensor data fusion. For outdoor tests, the GPS, inertial and encoder data are fused by using the Kalman filter. Figure 27 shows the test data and overlay of the data on Google Map in the court yard on campus.

Figure 27. GPS Localization.

Control

For an under-actuated car-like ground vehicle trajectory tracking control, we consider the 3 degree-of-freedom nonlinear vehicle rigid-body dynamics with nonlinear tire tracking force, nonlinear drag force and actuator dynamics. The uphill and downhill effects will be treated as load disturbances and will be overcome by closed-loop driving control. The control algorithm, which employs Trajectory Linearization Control (TLC) based on singular perturbation theory, has been used in IGVC 2018, as shown in [1, 3]. Compared with the old version of the control system, the one for IGVC 2019 has been updated by incorporating the reverse functionality [6] and improving the tracking precision [5]. Figure 28 shows the result of a hardware validation test of a rose-curve trajectory followed by a circle, where Figure 28a shows the water mark left on the ground, and Figure 28b shows collected data. It is noted that this test was with only on board inertial sensor, encoder and GPS or camera.

The hardware test results are shown in the on-line video [10].



(a) Ground water mask (b) Collected test data

Figure 28. Rose Curve Tracking.

7. FAILURE MODES, FAILURE POINTS AND RESOLUTIONS

Table 4 highlights the various failure points and modes for Pathfinder. It also highlights the strategy taken while designing the vehicle to mitigate failures where possible, and make failures easier to recover from. Lastly it covers the strategy for dealing with failures and recovering while out in the competition field. From the beginning of the design, care has been taken to modularize the vehicle and subsystems. This makes recovering from failures out in the field easier, provided there are backup components available.

Failure Points	Failure Modes	Design Strategy	Field Strategy
Electronic			

Electronic Sensors	Faulty sensors/connectors, interference, causing instability.	Modular sensors and high-performance connectors used.	Test connections, replace damaged components.
Onboard Computers	Computer faults (HW/SW), connection faults, data corruption.	Modular platform, high performance computers.	Diagnose issue, resolve or replace with backup.
Wireless Connectivity	Wi-Fi router/interface faults, interference from other networks.	Use of 5GHz for interference, high gain antennas for range.	Use different Wi-Fi channels, backup router.
Electrical			
Electronic Speed Controller (ESC)	Overheating or faulty, disabling vehicle.	ESC was chosen with high performance margin.	Frequent temperature check, replace if failed.
Electrical Components	Faulty or damaged components, causing vehicle malfunction.	Electronic subsystems are modular and replaceable.	Test connections, replace damaged components.
Electromechanical			
Steering Servos	Overheating or faulty, disabling vehicle.	Large high performance, high torque servos were chosen.	Replace if failed.
Drive Motors	Overheating or faulty, disabling vehicle.	Large drive motors used for additional performance margin	Replace if failed.
Mechanical Linkages	Steering linkages, drive motor mounts, gearbox may fail.	Metal linkages, secure fasteners used.	Attempt to fix, replace if parts are available.
Guidance (software)			
Control Algorithms	Freeze-up, or unintended results, causing undesired operation.	Follow best practice in software engineering, rigorous testing	Troubleshoot, utilize e-stop if loss of control.

In order to evaluate the failure points and modes, extensive testing was performed with Pathfinder. Because adding built-in redundancy was unfeasible, regular testing of the vehicle as a whole, in different environments was necessary. This method has already proved useful. Recently the wireless router failed, highlighting a previously unnoticed failure point, now a backup unit will be available. In last year's competition a single relay failed, preventing Pathfinder to be qualified. This year, only days away from the competition, both steering servo motors overheated and failed under an unusual operating condition where the steering wheels were stalled, even though the servos had been properly designed with ample margin for nominal operation. This event further highlighted the need for larger servos.

8. SIMULATIONS

Software simulations of the motion control sub-system and the guidance sub-system were performed using MATLAB-SIMULINK. With the help of the Quanser QUARC software, the SIMULINK program can be downloaded directly to the Q-Brain motion computer for hardware validation. Visual perception software was verified in Python using pre-recorded video. The cognitive state machine was also verified in Python using test cases.

9. PERFORMANCE TESTING

To ensure on-time integration of all subsystems and successful integrated hardware testing, subsystem and component tests have been conducted on the Pathfinder and a small prototype of Pathfinder. All the hardware tested on the prototype of Pathfinder can be directly integrated on the Pathfinder due to the built-in scalability and crosscutting ability.

The vehicle mechanical subsystem has been tested on pavement and grass field to validate that the required speed, climbing, and turning performances are met.

The Guidance (path planning), Navigation (motion sensing and localization) and Control (GNC) sub-systems were validated on the smaller prototype and the results have been published in [2]-[5] or submitted for publication as [6], [7]. A video of some relevant hardware demo cases, including line following and obstacle avoidance, can be viewed on line at [10].

10. PERFORMANCE ASSESSMENTS

Pathfinder has been tested to meet or exceed the following predicted performance specifications:

- Top Speed of 2.2 m/s or about 5 Mph.
- Able to climb a grassy hill with an incline of about 25 degrees with full load.
- The reaction time for line detection is under 0.1 s, and for obstacle detection is less than 0.15 s. This performance can be further improved by refining the code.
- The battery life has been tested to last about 45 minutes for cumulative operations.
- The sonar system can detect obstacles at about 0.15-2 m around the corners of the vehicle, while the depth camera has an effective range of no less than 6 m.
- The motion control system is capable of forward and reverse trajectory tracking. The guidance system has been tested for lane following, obstacle avoidance, as well as parallel and reverse perpendicular parking, which can be used when switch backs are needed. The vision system has been demonstrated to detect white lines and circles on pavement reliably. Detection on grass are not as reliable and are being improved.
- The onboard GPS without augmentation has a tested 3D accuracy of about 1.5 meters. The sensor-fused navigation accuracy has been demonstrated to be less than 0.1 m over a period of 2 minutes while running a complex rose-curve trajectory followed by a circle as shown in Figure 29.

Through the tests to date, the team has identified failure points and modes though extensive testing in multiple environments. In addition to failure points discovered from past experiments and logical thinking, recent tests revealed that the depth camera data can be corrupted by low-quality USB cables. The front steering servo motors were also damaged in an unusual pose. These failures prompt acquisition of high-quality USB cables and larger servos. Another unresolved issue is camera vibration on the grass, which significantly deteriorated the mapping precision. A gimbaled camera mount is being purchased in hope to alleviate the vibration. Proper tire pressures and anti-vibration by image processing technics will also be experimented.

In summary, we still need to resolve the issues with damaged steering servos, faulty USB cables, and camera vibration in the remaining days before the competition. We also need to perform extensive testing our line recognition capability on grass field. However, we are confident that this year we will be able to take part in the Auto Nav competition and hopefully to win.

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