Development of the SciAutonics / Auburn Engineering Autonomous Car for the Urban Challenge

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Executive Summary

This paper describes the vehicle and approach taken by Team SciAutonics / Auburn Engineering for the Urban Challenge (UC) in November 2007. We successfully participated in the Grand Challenges of 2004 and 2005 with our ATV-based vehicle RASCAL. For 2007, we continued to upgrade our sensor and control technologies in addition to adding a new platform – a Ford Explorer. The team includes SciAutonics LLC (Thousand Oaks, CA), Auburn University (Auburn, AL), Austrian Research Centers GmbH – ARC (Vienna, Austria), and ESRI (Redlands, CA).

A-priori routing and necessary rerouting over the network of roads/open areas provided in the RNDF will be provided by our ESRI team members. An artificial intelligence enables our vehicle to enhance its knowledge of road segments that have been driven over more than once. LIDAR and vision systems enable obstacle detection and recognize road markings. Significant software development was required for moving obstacle detection, traffic merging, and other challenges.

The team has a capable autonomous vehicle (RASCAL) that was used early in the development cycle for the testing necessary for the UC. The team has members with a skill set directly relevant to addressing needs for the UC over and above those required for the Grand Challenge series.

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Abbreviations

ATV – All Terrain Vehicle
COTS – Commercial Off The Shelf
DARPA – Defense Advanced Research Projects Agency
DGC – DARPA Grand Challenge
GC – Grand Challenge
GIS - Geographic Information System
GPS – Global Positioning System
IMU – Inertial Measurement Unit
INS – Inertial Navigation System
LIDAR – Laser Imaging Detection and Ranging
LLC – Limited Liability Corporation
MDF – Mission Data File
NQE – National Qualifying Event
RASCAL – Robust Autonomous Sensor Controlled All-terrain Land vehicle
RADAR – Radio Detection And Ranging
RNDF – Route Network Definition File
SVS – Stereo Vision System
UC – DARPA Urban Challenge
UCFE – Urban Challenge Final Event
UGV – Unmanned Ground Vehicle
UTM – Universal Transverse Mercator

Technical Approach, UC 2007

SciAutonics/Auburn Engineering has built a vehicle that will satisfy all of the objectives of the Urban Challenge, based on the extensive capabilities developed and experience earned while competing in the first two Grand Challenges.

Overview

The SciAutonics/Auburn Engineering team participated in both the 2004 and 2005 DARPA Grand Challenges. In the 2004 event, RASCAL completed approximately three-quarters of a mile; while in 2005, it was one of 10 teams selected early to compete in the challenge and traveled 16 miles of the course. The UC extends the objectives to the city environment. Many of the lower level sub-systems (such as navigation, vehicle steering/throttle control, and sensor interface) were directly transferred from RASCAL (although every sub-system underwent upgrades). The Urban Challenge requires a new higher level of system autonomy; a path planner to avoid obstacles over open terrain was not sufficient. While the path planner is still needed to avoid obstacles such as stopped cars, it must be governed by a higher authority that determines the best route between mission checkpoints and guarantees that all traffic laws are obeyed. Most of the difficulties in the UC lie in this higher level of control.

The objectives of the Urban Challenge are to build an autonomous vehicle that will:

- Plan a route through a series of widely spaced waypoints in an urban environment
- Drive that route, while obeying all California traffic laws
- Stay on established roads
- Avoid fixed and moving obstacles
- Re-plan a new route when the planned route is found to be impassable
- Drive across open regions
- Pull into and out of parking places

These objectives flow down into a series of required vehicle behaviors:

- Stably driving a planned route at speeds up to 30 mph, using differential GPS/IMU system and with limited GPS satellite visibility
- Sensing the actual location of established roads
- Sensing obstacles on the planned path, estimating the trajectory of moving obstacles
- Re-planning to avoid obstacles and change routes based on blocked roads

Existing Assets

SciAutonics' vehicle RASCAL successfully ran in both DGC 2004 and DGC 2005. In doing so, we assembled and/or developed the technology to:

- Plan a route through a series of waypoints
- Stably drive a planned route, using differential GPS, at speeds up to 40 mph
- Sense obstacles on the planned path
- Re-plan the path to avoid obstacles
- Integrate sensor data between noisy and conflicting sensors and over time

High Level Architecture

Our overall architecture is shown in Figure 1. The vehicle is at the bottom. On the lower right, sensors send data up a series of processing stages. On the lower left, actuators on the vehicle receive commands from the control logic. In the center is the Vehicle State Estimator, which continually makes optimal estimates of the vehicle's position, velocity, heading, roll, pitch, and yaw, based on inputs from the GPS, IMU, vehicle sensors, and obstacle sensors. The vehicle state estimates are used by all parts of the control system, including the Path Planner.

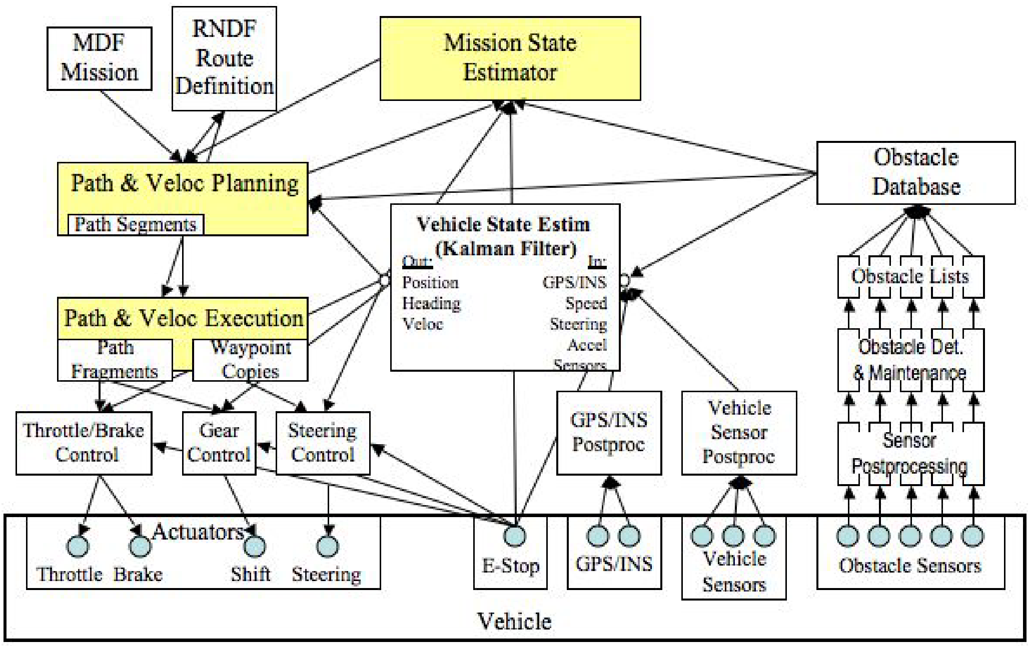

Figure 1. Overall vehicle architecture

At the top of the diagram is the Mission State Estimator. It determines what phase of a mission the vehicle is in and identifies when unique behaviors such as passing or parking are required. When the vehicle is driving in an urban environment, the key challenge that must be addressed is situational awareness. Not only must the vehicle follow a path and avoid moving obstacles, but it must also demonstrate correct behaviors depending on the situation. We treat each type of situation as a state and construct a state diagram to show the behaviors and transitions. A state table to address a basic part of the problem can be seen in Figure 2.

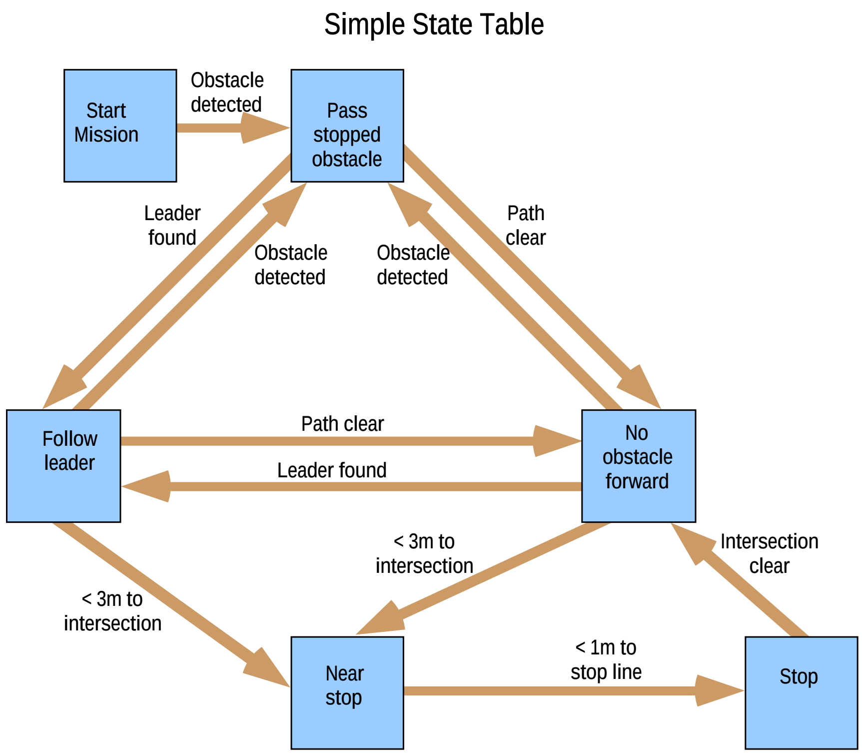

Figure 2. Example of state table

As an example of how the states would be used in the vehicle, consider the case where the vehicle is traveling in an area free of obstacles. In that case, it would be in the "No obstacle forward" state. The vehicle would stay on the road and in motion based on GPS and road identification sensors. If a stopped obstacle were detected on the path, the vehicle would transition to the "pass stopped obstacle" state. In that case, it would move out of the most likely lane to avoid the obstacle; when the obstacle is passed, it would move back into the lane (and back to the "No obstacle forward" state).

Design considerations

Sensors:

- High cost, high accuracy IMU vs. low cost, low accuracy
- LIDAR vs. camera vs. stereo vision etc.
  - Can use multiple systems
  - What does each system add to sensing capabilities?
  - What sensors to use in which situations
- Obstacle detection:
  - Performed separately for each sensor type rather than collectively for all sensors

Obstacle representation:

- Obstacle list vs. spatial map:
    - In this application, an obstacle list is more efficient in terms of memory and computational requirements and it allows tighter collaboration between sensor types (i.e. easier sensor fusion)

Software operating system:

- Linux vs. Windows:
    - Linux provides better isolation of processes and more consistent cycle times
    - Linux allows the use of Gazebo for simulation

Simulation:

- Using simulations (such as COTS Gazebo and Auburn's in-house) greatly reduces development time

Vehicle

The vehicle is a modified Ford Explorer. Power for sensors and computers is provided by heavy duty alternators. Multiple off-the-shelf computers provide the processing.

Figure 3. Entry vehicle

Vehicle Control

The vehicle was previously adapted for "drive-by-wire". It remains "street legal" and readily drivable on public highways.

Auburn University has implemented the vehicle controller used in the 2005 Grand Challenge on the Urban Challenge vehicle. They have a wealth of vehicle modeling and control experience with passenger vehicles, ATVs, farm tractors, semi-trucks, and large military vehicles. Therefore, the transition was relatively easy, requiring only slight modification to the vehicle model parameters in the controller. The controllers were modified to increase their capabilities to handle situations such as following vehicles (adaptive cruise control), parking, and queuing at stop signs.

Route Preplanning and Re-planning

The current RASCAL route planner was extended to deal with the additional requirements of the Urban Challenge.

a) Original features:
   1. Given a sequence of waypoints through a sequence of corridors, plan an optimally fast route, taking into account the vehicle dynamics, including roll over limits, acceleration and deceleration regions, etc.
   2. When obstacles are detected, modify the route to avoid them in an optimally fast manner while staying within the corridors.

b) New features
   1. Re-plan the route when sensor data indicates that the road diverges significantly from a straight line between waypoints.
   2. Re-plan a new route when the planned route is impassable.
   3. Lane change, three-point turn, pull in/out of a parking place.
   4. Avoid contact with moving obstacles.
   5. Stop and go at stop signs.

Route planning and re-planning thru the grid of urban streets is performed using ESRI's COTS ArcGIS Network Analyst: www.esri.com/software/arcgis/extensions/networkanalyst/index.html. Using Network Analyst's API and its rich object model, we built a custom application to interface with the Path Planner and Vehicle State server to determine new routes on the fly.

All streets traversed will be remembered so that if the vehicle must traverse them again, it will be able to anticipate the actual street location. Any discrepancies between the provided map (waypoints) and the drivable roads will be remembered.

Path Following With Limited GPS

The Urban Challenge will require vehicles to follow a path when GPS signals are limited or absent. The existing navigation system can operate reliably for several minutes without GPS but will be enhanced to handle issues common to city environments. Auburn University will integrate the following features into the existing navigation system:

a) Tightly Coupled GPS/INS Navigation: In an urban environment, the number of GPS satellites required for accurate differential operation may not be available. Auburn University's tightly coupled navigation algorithm will be implemented which combines the raw GPS carrier-phase measurements with the INS measurements, while taking into account vehicle's dynamic characteristics in order to improve the accuracy and robustness of the solution. This algorithm allows for improved performance when some (if not all) of the GPS satellites are blocked. The tight coupling also allows for faster reacquisition of lost signals after short signal outages if the receiver is aided with the solution. Therefore, tight GPS/INS integration can provide a means of improving the navigation by piecing together intermittent GPS signals as the UGV passes by trees or buildings. Tight coupling also allows the bandwidth of the phase lock loop used to track the GPS carrier signal to be decreased thereby increasing the GPS signal tracking capability. The improved signal tracking leads to an increased signal to noise ratio, which allows better calibration of the INS unit, reduces errors due to multi-path (which occurs in cluttered environments), and increases GPS signal tracking performance in high foliage areas (Kaplan, 2006). The tightly coupled algorithm will also use extensive knowledge of the sensors' parameters and characteristics. Auburn University has much experience with sensor characterization for navigation. If the sensors properties and behaviors are adequately known, the characteristics can be used in the navigation algorithm to minimize dead reckoning error by accounting for known sensor errors.

b) Object-assisted GPS/INS Navigation: When GPS data is inaccurate or missing altogether, it is possible to drive a road by navigating relative to the vehicle's surroundings. For example, curbs, fences, buildings, or signs can be identified with a distance and angle using the LIDAR and/or vision measurements. These measurements, relative to the vehicle, can be incorporated into the tightly coupled navigation algorithm to correct inertial errors with and without GPS, and therefore a lesser reliance on GPS is needed. When waypoints do not provide an accurate map of the road, the vehicle can still navigate relative to a corridor defined by identified objects surrounding the vehicle (Travis, 2006).

Road Following With Limited Waypoints

The Urban Challenge requires vehicles to follow roads that are indicated by only occasional waypoints. ARC has developed algorithms to track lane markings, road edges and curbs for highway vehicle navigation systems. The system provides lateral offset measurements as well as vehicle orientation measurements without GPS. Additionally, Auburn University is currently combining vision measurements from a Lane Departure Warning (LDW) camera with GPS/INS/database information using a fully instrumented sedan (Clanton 2006). The LDW camera provides lateral position and orientation of the vehicle in the lane similar to the system provided from ARC. Preliminary data collected using the LDW camera and GPS/INS measurements at Auburn's test track have validated this approach.

Obstacle Detection and Avoidance

In the previous Grand Challenges, we demonstrated software that detects obstacles along the vehicle's path (using LIDAR and vision sensors) and replans the path to avoid them.

Moving Obstacles

Our current obstacle detection and avoidance software also deals successfully with most slowly moving obstacles. However, for fast moving obstacles that are on an intercept course with our vehicle, we are adding the following features. For an obstacle that appears to be moving from successive measurements, we establish a track file that predicts its future path. If this path will intersect our vehicle's path, then one of a number of behaviors will be used. If our vehicle is at an intersection, it can wait for the other vehicle to pass. If our vehicle is moving, it can adjust velocity or heading to avoid the collision. If our vehicle is changing lanes, it will wait until the other vehicle passes.

Sensor Suite

As indicated above, sensors are needed for both localization (GPS, IMU, etc.) and perception (obstacle and road detection). A strategy of redundancy will be employed to provide measurements from some sensors when others are not available or in the event of the failure of a particular sensor.

Several sensors are used for vehicle localization and navigation. The cornerstone for vehicle localization is a single antenna Navcom SF-2050 DGPS receiver with Starfire satellite-based corrections provided by Navcom. It generates unbiased measurements of position (north and east), velocity (north, east, and up), and course at 5 Hz. With the corrections provided by Navcom, this GPS receiver is capable of producing position measurements accurate to less than 10 cm. However, the output rate of the receiver is too low to adequately control the vehicle. To obtain high update rate measurements, it is accompanied by a Honeywell HG1700 tactical grade 6 degree of freedom IMU that measures translational accelerations and angular rates at 100 Hz. A NovAtel Beeline RT20 dual antenna GPS system is used for obtaining the initial vehicle orientation, as well as longitudinal and lateral velocities.

The vehicle uses several types of environmental sensors for obstacle and vehicle avoidance: LIDAR sensors and the ARC stereo vision sensor. The capabilities of these sensors overlap to provide the redundancy desired to protect against sensor failure and improve reliability of measurements.

We will use scanning LIDARs for object location and ranging. They will detect both static and moving obstacles and provide the data for moving object track estimation. They will also measure the distance to other vehicles in lanes. Each of the LIDARs uses a class 1 (eye safe) infrared beam that is reflected off of a target.

Targets in the overlap region in front of the vehicle will be fused using software. The vertical LIDAR will prevent loss of targets due to pitching of the vehicle caused by road roughness as well as providing a means of detecting and filtering out ghost echoes from the road. These will be used for detecting objects that are off to the sides of, or directly behind the vehicle. They will be used for maintaining separation from other vehicles when passing, for detecting obstacles and other vehicles in open areas and parking lots, and for backing up. Each of the LIDARs is pre-aligned to optimize coverage of the terrain around the vehicle. The frame update time is 13 ms for the SICK LIDAR. At a speed of 20 mph, the vehicle will travel ~0.11 m between updates. The latency when tracking targets in successive frames may be as much as 39 ms. The range for practical targets is assumed to be ~50 m.

As a near- and mid-range (4 m < R <20m) obstacle sensing system, an embedded stereo vision system developed by Austrian Research Centers – ARC, is used. This stereo vision systems bases on the system used at DARPA Grand Challenge 2005 and is now adopted and extended based on the new requirements for the Urban Challenge.

The embedded stereo vision sensor detects objects up to a distance of 20 m and also provides information about lane marks and lane borders. The stereo vision sensor consists of a pair of Basler A601f monochrome cameras with a resolution of 656 (H) x 491 (V) and a quantization of 8 bits/pixel. The frame rate of the sensor is 10 frames per second to cope with the real-time requirements of the vehicle. Both cameras are connected by a 400MBit-FireWire network to an embedded vision system. That system is based on a Texas Instruments TMS320C6414 DSP running at 1GHz and the operating system is DSP/BIOS II from Texas Instruments. The embedded vision system is responsible for the synchronous acquisition of both images, for execution of the computer vision algorithms, and the communication with the vehicle central brain via an ethernet interface using UDP sockets. The whole stereo vision sensor is protected against rain, dust and sunlight by a special housing.

Figure 4. Embedded vision system (left) and external stereo sensor head (right)

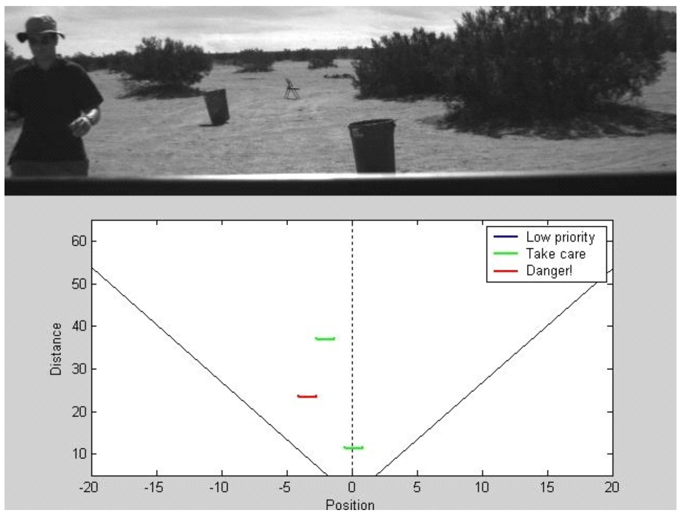

Figure 5. Result of obstacle detection

The main task of the stereo vision sensor is the detection of obstacles, lane marks and lane borders in front of the vehicle. For obstacle detection, a fast stereo matching method is used. Furthermore, the bouncing of the vehicle is predicted and compensated in the stereo images to improve detection of obstacles and lane marks. For extraction of lane marks and lane borders, only the right camera image is used. The image is searched on different levels of resolution for significant markings and borders on the road. Identified lane markings and borders are classified, labeled and reported back to the vehicle brain. Additionally, the vision sensor contains of a debugging interface for real-time logging of the right sensor input image and the extracted obstacles, lane marks and borders and some internal states for field-testing and evaluation.

Table 1. Sensor summary

Sensor	Range	Horizontal FOV	Vertical FOV
Forward horizontal LADAR	50m	180	1
Rear horizontal LADAR	50m	180	1
Vertical LADAR (on rotary mount)	50m	1 (270)	100
RADAR (on rotary mount)	100m	12 (290)	10
Horizontal LADAR (on tilting mount)	50m	180	1 (30)
Stereo Vision Sensor	20m	40	30

Obstacle Database

These sensors provide the capability of sensing the presence of objects over a full 360° field around the vehicle. This allows the vehicle to back up (e.g. exiting parking spaces, three point turns), and drive in open spaces. The range allows the vehicle to detect other vehicles that are at least far enough away when pulling into a lane to safely pass a vehicle or for pulling into a roadway at an intersection.

The output of each of these sensors is fed to sensor-specific feature extractors and obstacle detectors. A sensor consistently seeing an obstacle and multiple sensors seeing an obstacle will add to the "cost" of passing through that obstacle. Obstacles that are only seen a single time by a single sensor will have a lower cost. Obstacles are then collected in the global Obstacle Database. The Path Planner decides which obstacles lie in the vehicle's intended path or will intersect it in the future. If necessary, an alternative path is computed, avoiding a collision with the obstacle.

Vehicle Safety

Vehicle safety and the safety of participants and evaluators will be paramount. In addition to providing all the required features such as an e-stop and appropriate warning lights and sounds, all software is designed with fail-safe features based on our previous autonomous vehicle experience.

Simulation

We have developed a full simulation of our vehicle and its software, using Gazebo (Koenig & Howard, 2004), a multi-robot simulator for outdoor environments. Simulation greatly accelerates the development process. Multiple team members can run tests in simulation in a minute on laptops vs. an hour for a single test using the actual vehicle. We can replay recorded sensor data into the simulation and quickly test numerous processing algorithms on it. Improved algorithms can then be run on the physical hardware to test their validity and accuracy.

Additionally, Auburn University has developed many in-house simulations for the vehicles and navigation sensors. These simulations are used to test different navigation algorithms/sensor combinations, as well as try various control methods and tunings.

Testing

Facilities exist or are available in both California and Auburn University to test the system in environments as similar to the final event as possible. The individual sub-systems were developed independently by each of the team members, with continuous communication to ensure proper sub-system integration. Throughout the development of the system, the team members tested the system as a whole in increasingly accurate event environments. These whole system tests will ensure that the sub-systems work together correctly; extended duration testing will also be performed to guarantee system robustness.

Past Results and System Hardening

The SciAutonics/Auburn Engineering team has made it to the final event in each of the previous two Grand Challenges. In both events, our run was stopped early because of hardware failures. In 2004, a hard drive failed, while in 2005 a USB hub overheated. The new platform should mitigate the hardware robustness issues a great deal; it has an enclosed cockpit (as opposed to the previous RASCAL platform). The enclosed space is a much less harsh environment for the computing equipment. However, we realize that simply changing the vehicle is not enough to ensure a robust system. More time will be spent stress testing individual components and the system as a whole to ensure the platform is rugged enough to survive the challenge.

The Case for SciAutonics/Auburn Engineering

The SciAutonics/Auburn Engineering team has a portfolio of experience based on our participation in two prior Grand Challenges and over 100 years of experience in carrying out government funded sensor- and vehicle-based research programs.

Team members ESRI and Austrian Research Centers GmbH - ARC provided the use of their proprietary hardware and software. Additional added value will come from the unpaid volunteer labor of many individuals from all parts of the team.

After successful completion of the Urban Challenge, the team will have an autonomous driving solution that will be readily transferable to a variety of vehicles, both military and commercial. By working with both our current partners (such as ATV Corp., the manufacturer of RASCAL) and future partners, we will be able to transfer our solution to additional vehicles.

Results and Performance

Currently we have tested a large portion of the basic behaviors at speeds of 4m/S. Extensive testing at higher speeds and of the advanced behaviors is planned in the months leading up to the Urban Challenge. Some specific outcomes and analysis of the testing so far:

Track following – The average error in following a GPS defined track is 0.3 meters. The primary source of this error is steering mis-initialization. When commanded to drive straight an offset is present. The control software correctly follows the path, but the offset results in following the track with the 0.3 meter offset. The mis-initialization is caused by the limit switches not always triggering at the same point due to ground irregularities and suspension compliance. Two possible routes to correcting this issue are to dynamically determine the offset and correct it in the control software or to add a more accurate sensor to the steering that can be calibrated once and does not need to be re-initialized for each run. The implementation on the Ford Explorer is designed to eliminate this mis-initialization.

Static obstacle avoidance – Obstacle avoidance is improved over prior years. Testing to date has consistently avoided static obstacles. The current avoidance is not always as smooth as desired. A human driver scales their response based on need. The current algorithms are quite aggressive when implementing the steering and velocity corrections. Algorithms that are smoother for the cases where applicable are planned.

Moving obstacle avoidance – Testing has been limited to intersections. The robot is stationary while obstacles move in front of it. These are correctly processed for determining the robot behavior.

Vehicle speed – 4 meters per second has been used for most testing to date. We have experience at speeds up to 14m/S with prior software, but have limited the speed for the current testing for safety (it is a lot easier for a human to correct an error at 4m/S) and for practicality (our most accessible test sites have a limited size for achieving the higher speeds). Scaling to higher speeds (10-12 m/S) is expected to be straight-forward based on past experience. Higher speeds (14-16 m/S) will pose additional challenges as the needed sensor range is near the limits of our current sensor suite.

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