1. Introduction

The National Defense Authorization Act for Fiscal Year 2001, Public Law 106-398, Congress mandated in Section 220 that “It shall be a goal of the Armed Forces to achieve the fielding of unmanned, remotely controlled technology such that… by 2015, one-third of the operational ground combat vehicles are unmanned” [1]. In response to the congressional mandate, the Defense Advanced Research Project Agency (DARPA) initiated the Grand Challenge competition. The goal of the competition was to promote and accelerate research and development of autonomous robotic ground vehicles that can navigate itself in off- and on-road terrain. The motivation is to develop technologies that will keep military personnel off the battlefield and out of harm’s way.

The first competition took place on March 13, 2004 and the course was approximately 130 miles of desert terrain from Barstow, CA to Primm, NV. There were 15 participants in the competition but no team was able to complete the course. The competition was repeated on October 8, 2005 with 23 participants and 5 teams were able to complete the course [2, 3]. The Stanford Racing Team won the $2 million prize with a winning time of 6 hours and 53 minute [4]. In May 2006, DARPA announced the 2007 Urban Challenge competition which requires autonomous ground vehicles maneuvering in a mock city environment, executing simulated military supply missions while merging into moving traffic, navigating traffic circles, negotiating busy intersections, and avoiding obstacles [5].

In response to this announcement, NJIT has assembled a team of students, faculty, and industry experts to undertake the 2007 Urban Challenge. The proposed program will allow the NJIT team, Highlander Racing, to design and develop a low-cost, adaptive and robust autonomous vehicle that can navigate in a complex urban environment. The innovation of the NJIT system lies in its human-like ability that can make judgments based on the vehicle’s surroundings. This system is able to respond with the speed and accuracy needed to complete all the objectives of this competition safely and effectively.

The goal of this paper is to provide an overview of the initial architecture and design of the NJIT autonomous vehicle. In addition, this project presents a number of education and management related problems such as administration of a large student-centered project, interaction of diverse and multidisciplinary subgroups, recruitment and supervision of team members, and relationship-building with sponsor companies. In this paper, our experience in running the NJIT Highlander Race Team will be reported along with findings pertaining to improvement of the team dynamics.

2. System Architecture and Overview

The unique demands of the 2007 Urban Challenge have inspired Highlander Racing to design a system with a human-like ability to make judgments based on the vehicle’s surroundings. This system is able to respond with the speed and accuracy needed to complete all the objectives of this competition. It embodies a simplified data flow system that allows more pressing situations to be handled very quickly.
and correctly. While most of the processes will be running in parallel based on their respective immediate inputs, a feedback control data flow will continuously update the system priorities to adapt with the environment and in their decision making. The overall system architecture and its data flow are illustrated in Figure 2.1.

Figure 2.1. Overall system architecture of Highlander Racing.

In the Environmental Awareness Module, the outside world is continuously monitored by an array of sensors whose outputs are weighted and fused according to the current mission state and combined to provide static and dynamic mappings of objects. The Route Planner and Field of View Planner can handle the objectives of advanced navigation by dynamically planning appropriate paths to complete a mission. The Immediate Planner handles the objectives of realistic traffic navigation by providing an on the fly response to surroundings and mission objectives, and regulates output fed to the Control System. The Control System then translates the trajectory information into usable commands for the vehicle’s servos. To keep up with the demands of real driving in unknown environments, the system dynamically plans paths parallel to execution to optimize a “performance index” function ensuring the successful and timely execution of mission priorities.

A hybrid approach of knowledge-based model and environmental awareness to vehicle navigation is used in all planning. The model-based reasoning allows the planning system to determine how the vehicle should react under certain limiting conditions. The decision rules in the model (besides certain offline-computed rules) are also updated during the mission run time via continuous learning to improve the vehicle’s performance and efficiency. For example, by finding the deviation between the calculated and actual path trajectories and extrapolating feedback data, (frequency of turns, distance between stops, etc.) the system can adapt to a new environment, new vehicle platforms, loss of select sensors, and vehicle damage. The Environmental Awareness module provides the most accurate view of the environment around the vehicle. Should the sensor data become unreliable, this hybrid approach will allow the system to temporarily fall back on the knowledge-based model and still operate the vehicle correctly. This approach also provides ease of deployment in new and inexperienced theaters.

The system design is modular providing the ability to easily replace and improve modules without affecting the other parts of the system. Redundant and complimentary sensors allow completion of the mission under partial sensor failure. This unique topology of the system allows for distributed computing and quick recovery from partial system failure. This system will reconfigure the subsystems or sensors, should they fail, to shift the workload, completely or temporarily, to other modules, thereby,
making this system robust to failure. This system is designed to be low cost and intended for easy replacement and mass production purposes. Furthermore, the system uses off-the-shelf components with proven reliability, easy duplicability, and can be rapidly field repaired.

2.1 Environmental Awareness Module

The Environmental Awareness Module (EAM) is designed to work in parallel on either acquiring data and/or processing it. The Pre-Processing Sensor Data module is used to filter and pre-process the sensor data for noise reduction to be used for better perception. The Positioning module calculates the vehicle’s current position and orientation, as this information is critical for almost all systems. The Object Detection/Tracking System (ODTS) uses the pre-processed sensor data to define objects and, if needed, can provide object tracking information. This data is also used for road detection and path panning as described below. The Road Boundary Detection Systems (RDBS) relies on machine vision to detect road boundaries.

The EAM relies on sensors to identify its present location, detect and track obstacles, and identify road boundaries. It is important to have a variety of sensors that are both redundant and complementary. Our vehicle will be equipped with a large array of sensors to accomplish the mission. The sensors that we will be using are: RADAR (Radio Detection and Ranging), LADAR (Laser Detection and Ranging), single vision camera, stereoscopic camera, ultrasound sensors, GPS (Global Positioning System), wheel encoders. To minimize lead time and cost, commercial off the shelf units are used.

2.1.1 Perception

The LADAR system will be used primarily for obstacle detection. Because of the high-resolution output, we will be able to differentiate obstacles with relative ease. We also plan to use a ground scanning LADAR unit for lane detection. The drawback to LADAR is in the reflections. The Radar and Ultrasound sensors will be used as bump-detection mechanisms. These will be low-range systems that detect the presence of objects.

The vision systems will be used for road detection as well as obstacle avoidance. Also, since the DARPA specified waypoints would be sparse and not guaranteed to be accurate, our vision systems will provide us with the visual cues needed to maintain our position.

2.1.2 Positioning

To keep track of our position and orientation, we will be relying on DGPS (Differential GPS), an electronic compass, and an Inertial Measurement Unit. In addition, there will be wheel encoders to keep track of slip conditions and to acquire maneuvering information. The wheel encoders will augment the accuracy of our current position and will provide us with some guidance when GPS signals are blacked out or otherwise unavailable.

2.1.3 Pre-Processing Sensor Data

This System is composed of the input from several different sensors for pre-processing for noise reduction and validation. It takes a specific sensor data and maps it to a common world coordinate system. Once the sensor inputs have been corrected, it is put on the internal data bus and sent to the Object Detection/Tracking System and Road Boundary Detection System.
2.1.4 Object Detection/Tracking System and Road Boundary Detection System

The primary detection/tracking sensors used in the vehicle are LADAR, RADAR, machine vision (cameras) and ultrasound sensors. Each sensor generates object data in a coordinate space referenced to their mounting position on the car. These sensory data are then correlated with the global coordinates using DGPS positioning and passed onto other systems that require the global object data.

Object Detection: Static object detection (car, human, etc.) is performed by fusing sensory inputs from LADAR, RADAR, machine vision (cameras) and ultrasound sensors. Data fusion must be intelligently done as each sensor has a different reliability factor under different conditions. To this end, sensory data are weighted (using fuzzy logic) differently under changing situations. This approach of data fusion allows the development of a model for each sensor and augmenting the model as necessary with the actual reliability in real conditions.

The sensors (except machine vision) deployed on our vehicle do not have the capability to track objects. To augment this, we have both stationary and movable cameras to detect objects. Object tracking is achieved by using optical flow (and Kalman Tracking) [6] on consecutive image frames. Any detected moving object and its velocities are then broadcasted to other required planner systems.

Road Detection: Road Detection is done by machine vision and LADAR. Machine vision processes the frames (with edge and color detection algorithm) to obtain the road edges. As mentioned earlier, an additional LADAR pointed downwards to the road is used for two purposes, detect objects and detect road boundaries. We are also considering using photodetectors mounted and pointing onto the road surfaces to detect when we are changing lanes and also to detect nearby lanes.

2.2 System Model

Figure 2.2 illustrates our overall system model. The planning module consists of three levels of planner arranged hierarchically: Route Planner (RP), Field of View Planner (FOVP), and Immediate Planner (IP). The Control System accepts inputs from IP and commands for the vehicle’s servomotors. There are two additional modules shown at the bottom of Figure 2.2.

Adaptation Process (AP): It is used to effect the changing of the model learning process. To ensure adaptability to different conditions, each module of the vehicle will be equipped with an AP that is capable of learning from environmental and other changes.

Priority Analyzer (PA): It analyzes (and thereby acting on) the mission criteria. The PA is a module that regulates the rules that the system has to follow and is allowed to break. The priorities are arranged so as to (1) avoid collisions; (2) complete the mission; (3) minimize penalties. The PA module will allow for minor infraction of certain traffic laws if they help to meet one of the goals. Of course, the infractions will be weighted as to minimize the penalties.

2.2.1 Route Planner

The Route Planner (RP) performs the general planning using the mission goal and generates a relevant route from the map with a set of accompanying directions. The RP functions in a way that is analogous to online map service such as Google Map but appropriately zoomed to the street level. As with most map software, RP will also define a database containing a network of streets based on the RNDF (Route Network Definition File). This database will be dynamically updated as more data are collected related to the condition of the road. RP will receive as input a starting waypoint and an end waypoint and will output, a map of the route between the two points with corresponding set of directions.
Figure 2.2. Highlander Racing system model.
Map: The map used by RP is initially based on the RNDF. As the car travels, feedback from the immediate planning system will update the map dynamically as needed. This will occur if the actual street conditions differ from the RNDF due to conditions such as a road blockage. The map will also be useful in the event that GPS coordinates of the road are not available or are delayed. The other planning systems will compensate and ultimately update the vehicle’s own map of the city with the correct information.

Planning: To find an optimal route that takes into account the approximate travel times based on speed limits, intersections/stops, other important road data, physical capabilities and limitations of the car. These calculations will be performed by a variation of Djikstra’s search algorithm [7].

Errors: If the vehicle encountered an error in the path, such as an impassible situation, a new path would be created and sent to the next stage in the program flow. If the car’s properties change because of damage or there is a change in situation (such as low gas level), the RP algorithms will adapt to the situation and continue to optimize the paths based on the car’s current status and situation. Figure 2.3 illustrates a situation where the RP will plan a U-turn due to road blockage.

Outputs: This system will create the city scaled path for the Field of View Planner to execute. The FOVP needs to know information about the roads the vehicle will be traversing and the intersections it will encounter. This will be provided as an ordered list of waypoints and control points. These points originate in the map defined by the RNDF and are updated by the immediate planner. Along with these points is the data about speed limits and other known and relevant road information.

2.2.2 Field of View Planner

The functioning of this system is parallel to a human’s approach to driving. The FOVP interprets the directions and road information from the RP and decides what to do next on a large scale. It is primarily concerned with avoiding stationary objects and hitting the mandatory waypoints that are included in the route. We are using an in-house algorithm that will help find the intermediate FOV-waypoints. It checks if there are any static objects in the rough route obtained from the RP and passes a more detailed path to IP.

If there are no objects in the coarse route supplied by the RP, the FOVP generates a more detailed path for IP to confirm. To perform these checks, FOVP must first check the car’s field of view; hence the name FOVP. It first polls the RBDS to find out the exact location of the road. The vehicle’s current position is also obtained from the GPS data. By correlating these two inputs with the road map provided by the RP, the current position within the map from the RP can be determined. The ODTS is then polled for new data, which it uses to generate a more detailed point-based path for the Immediate Planner.

If the vehicle is traveling out of the lane or an object is detected that either blocks the desired path or poses a threat to the completion of the mission goals, the FOVP is responsible for deciding how to...
react. On the other hand, if a moving object suddenly comes into play, the Immediate Planner will take care of that and the FOVP does not need to react very quickly.

2.2.3 Immediate Planner

The Immediate Planner (IP) is differentiated from the FOVP by its range and intelligence. It is needed for the following reasons:

1. The vehicle is at utmost danger from near-by objects. At speeds around 30 mph, FOVP cannot react to fast moving objects and re-plan the whole path to the next RP waypoint.
2. The FOVP has only a coarse view of the vehicle trajectory.
3. Computing resources for the FOVP is limited due to it is difficult to parallelize FOVP’s logic.

The goal of IP is to find effective paths to the next FOV waypoint such that moving objects can be avoided. Using the static object in sight the FOVP selects ‘optimal’ FOV waypoints to avoid the objects and reaches the next RP’s waypoint. Based on the current priorities, the IP will also account for conditions such as lowest cost in terms of breaking penalties, reducing risks etc.

IP will then segment the road into smaller parts so that a trajectory analysis can be done. Such segments are as small as <1m and can be as large as 10m depending on the velocity of the vehicle and the state (merge or straight) of the road. Each of these small segments is analyzed for possible trajectories that can be taken based on vehicular kinematics and dynamics (safe turning radius, current direction and speed). As IP can generate multiple trajectories that satisfy the above conditions, the following criteria are used to select the best trajectory:

1. Obstacle avoidance: Obstacle avoidance is accomplished by ensuring that the minimum width of the car on a trajectory does not intersect any static object or the possible trajectories of the dynamic objects. We will also take into account the risk of hitting an object. For example, the car will be able to make a trajectory within touching distance of another car, but with a risk that if the execution of such a trajectory is flawed, an accident will occur.
2. Minimum possible rule breaking: Rules are time penalties imposed by DARPA, such as crossing a solid double line or a striped double line. Such rules are stored in a Rule Database in descending order of severity.
3. Minimum deviation from the FOV waypoint: The immediate goal is to encounter a FOV waypoint. Thus a trajectory with more deviation would be less preferred than a straighter trajectory.
4. Possible trajectory with safe limits of vehicular dynamics: An extreme turn is bound to cause a rollover. Due to the physical constraints many vehicles cannot be trusted for near-limits trajectory and so are not preferred.
5. Time Constraints: A merge would require a time constraint compared to motion in open road. We propose a numerical measure called the Performance Index that will define the viability of such a trajectory.

A performance index (PerfI) is formulated to compare multiple trajectories based on obstacle avoidance, rule breaking, deviations and limits of vehicle kinematics and the optional timing constraints. The goal of the IP is to find the best trajectory by minimizing PerfI. This process is executed continuously in real time.

2.2.4 Control System
The basic function of the control system will be to control the vehicle’s steering, acceleration, braking and shifting mechanisms. The design of the control system will optimally match the vehicle dynamics. The control system will receive its input from the IP and using the AP to vary its internal parameters to match its current situations.

**Output Regulator (OR):** Besides controlling the servomotors, the OR will also implement the DARPA mandated E-Stop system. The E-Stop device will be connected directly to this regulator and any commands that are issued to the E-Stop will be interpreted directly by the OR. This reduces any lag in following the E-Stop commands and also ensures that the interrupt from the E-Stop is executed at the lowest level, thereby not being affected by any system faults in the rest of the system. The OR receives motor positions from the Control Path Interpreter that carries out feedback/feedforward control functions for improved transient, steady state accuracy. Our model-based method ensures high performance by considering linear dynamics as well as nonlinear effects such as saturation, friction, and hysteresis.

**Control Path Interpreter (CPI):** This module receives control trajectories (from the IP) that have been selected for their ability to complete the required mission. The function of the CPI is to convert these trajectories into realizable motor positions. The trajectories are first quantized into a series of discrete waypoints. Based on the heading deltas between the waypoints, the motor reference positions are selected and fed to the OR. The acceleration and braking systems work in harmony to ensure proper and fluid speed control. The speed is absolutely limited by the RNDF speed limits in sections and is further limited by the heading deltas between waypoints to ensure safe operation of the vehicle.

### 3. Sample Scenario

In this section, we will outline a typical scenario that we may encounter in the Urban Challenge and describe how our system will resolve the situation. All the images and processing results are obtained using our existing equipment. The scenario described is a vehicle traveling down a narrow alley and then turning right. Upon turning right, the vehicle encounters an obstacle and successfully avoids the obstacle. This scenario is shown in the following time lapsed photos:

![Image](image-url)

**Figure 3.1.** Time lapsed photos of the scenario where an obstacle (a car) is to be avoided.

Our system will carry out the following steps:
1. The RBDS detects the edges of the road as indicated by the green lines in Figure 3.2. The RBDS would synchronize the input it receives from the DARPA-supplied maps and the coordinates of the detected road boundaries. The road width, lane-width and other parameters are also recognized by the detection system.

2. The FOVP takes over and plans the immediate trajectory based on the sensor’s field-of-view. FOVP avoids static objects and plans the trajectory only slightly in front of the vehicle. This trajectory is calculated based on an optimization between the parameters of distance, speed, feasibility, and accuracy (Figure 3.3).

3. The IP calculates arcs that are directly relevant to the vehicle’s immediate decision-making process. IP generates a series of arcs that the vehicle can take immediately. This is limited by the current speed of the vehicle as well as the current road conditions. For example, if the AP has detected that the road conditions are prime for slipping, the set of possible arcs will be restricted.

Figure 3.2. Road detection and trajectory generation.

Figure 3.3 illustrates how the LADAR data can be used to detect obstacles. The blue blobs shown on the right correspond to obstacles in the scene.

Figure 3.3. LADAR data showing obstacles.

4. Education Implementation and Impact

Different from other competing teams, the NJIT Team is a student centered and student-led effort. As such, planning and organization are critical to proper execution of tasks and program objectives. Even though the team members are non-paid volunteers, their effort is recognized and indirectly compensated by course grades and credits via, e.g. senior design projects. At the kick off meeting in September 2007, two student team leaders were elected from the remaining members of the previous year’s DARPA Grand Challenge team. The student team leaders’ responsibilities include: organizing team meetings, communication, and integration of technical efforts. A panel of faculty advisors from electrical and computer engineering as well as mechanical engineering was assembled along with an industry advisor, thereby providing technical leadership in areas of automation/control, guidance/navigation, image
processing, and path planning. The next step was team member recruitment where information pamphlets were distributed along with a video presentation. Typical outreach events included:

- Student dormitories
- Student clubs
- Introduction to Engineering classes
- Senior Design classes

In addition to these efforts, flyers had also been posted around campus to spread information about Highlander Racing team to interested candidates. Male involvement with Highlander Racing had been very heavy, thus there was a strong focus on recruiting female members. The faculty advisors and student leaders had been working with undergraduate advisors as well as the Society of Women Engineers, to encourage interest in the female population for Highlander Racing.

After the recruitment process, the new team members were interviewed to assess their interest, backgrounds, and levels of commitment. Based on the results of the interview, each new recruit was assigned to a veteran team member in order to aid the learning of the different aspects of the project. Moreover, this initiation process allowed him/her to better adapt to the team’s chemistry. Initially, the new recruit learned and documented the different systems. Once the recruit became more comfortable with the environment and the project, he/she was assigned a technical task.

Highlander Racing provides students with an invaluable experience. On a personal level, it allows members to be a part of a team, retain a sense of camaraderie, and meet other students with similar interests and goals. Furthermore, the satisfaction of seeing instantaneous results instills confidence, motivation and pride [8]. On a university level, students can enjoy award opportunities and recognition from NJIT and administration. The hands-on practical experience employs applications learned in the classroom and applies it to something tangible. Highlander Racing is an extension and expansion of complex engineering concepts. Professionally, Highlander Racing is an outstanding resume-builder. The national contest is well recognized and its reputation is highly regarded. Students can boast about working within a team as well as the intense practical experience they acquired while working on this project. Outstanding team members are acknowledged and rewarded publicly. For example, during the NJIT senior design presentations, outstanding members of Highlander Racing are recognized.

5. Bibliography