Chapter 2
The State-of-the-Art in the USA

2.1 Introduction

The field of intelligent vehicles is rapidly growing all over the world, both in the diversity of applications and research [3, 8, 18]. Especially in the U.S., government agencies, universities, and companies working on this hope to develop autonomous driving entirely or in part for safety and for saving more energy. Many previous technologies, such as seat belts, air bags, work only after a traffic accident. Only intelligent vehicles can stop traffic accidents from happening in the first place. Therefore, DARPA has organized the Grand Challenges and the Urban Challenge from 2004 to 2007, which remarkably promoted the technologies of intelligent vehicles around the world. Hence, this chapter presents an overview of the most advanced intelligent vehicle projects which once attended either the Grand Challenges or the Urban Challenge supported by the DARPA in the USA.

2.2 Carnegie Mellon University—Boss

The research groups at Carnegie Mellon University had developed the Navlab series [8, 17], from Navlab 1 to 11, which include robot cars, tracks, and buses. The Navlab's applications have included Supervised Classification Applied to Road Following (SCARF) [6, 7], Yet Another Road Following (YARF) [12], Autonomous Land Vehicle In a Neural Net (ALVINN) [11], Rapidly Adapting Lateral Position Handler (RALPH) system [16]. In addition, Sandstorm is an autonomous vehicle which was modified from the High Mobility Multipurpose Wheeled Vehicle (HMMWV) and competed in the DARPA Grand Challenge in 2005. The Highlander is another autonomous vehicle modified from HMMWV H1 which competed in same competition in 2005.

Nevertheless, the latest intelligent vehicle is the Boss system (shown in Fig. 2.1) which won the first place in 2007 Grand Challenge [18]. Boss combines various active and passive sensors to provide faster and safer autonomous driving in an urban

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Fig. 2.1 The intelligent vehicle, named Boss, developed by Carnegie Mellon University's Red Team (published courtesy of Carnegie Mellon University)

environment. Active sensors include lidar and radar, and passive sensors include the Point Grey high-dynamic-range camera. The following functional modules were implemented on the Boss vehicle:

1. Environment perception: Basically, the perception module provides a list of tracked moving objects, static obstacles in a regular grid, and vehicle localization relative to roads, road shape, etc. Furthermore, this module consists of four subsystems, moving obstacle detection and tracking, static obstacle detection and tracking, roadmap localization, and road shape estimation.
2. A three-layer planning system consisting of mission, behavioral, and motion planning is used to drive in urban environments. Mission planning is to detect obstacles and plan new route to its goal. Here, given Road Network Definition File (RNDF) encoding environment connectivity, a cost graph guides vehicles to travel on a road/lane planned by the behavioral subsystem. A value function is calculated to both provide the path from each way point to target way point, and allow the navigation system to respond when an error occurs. Furthermore, Boss is capable of planning another route if there is a blockage.

The behavioral subsystem is in charge of executing the rules generated by the mission planning. In details, this subsystem makes decisions on lane-change, precedence, and safety decisions on different driving contexts, such as roads, intersections. Furthermore, this subsystem needs to complete the tasks, including carrying out the rules generated by the previous mission planner, responding to abnormal conditions, and identifying driving contexts, roads, interactions, and zones. Furthermore, these driving contexts correspond to different behavior strategies consisting of lane driving, intersection handling, and achieving a zone pose. The third layer

Fig. 2.2 The Stanford University's intelligent vehicle Junior that was the runner-up in the 2007 DARPA Urban Challenge (published courtesy of Stanford University)

of the planning system is the motion planning subsystem which consists of trajectory generation, on-road navigation, and zone navigation. This layer is responsible for executing the current motion goal from the behavior subsystem. In general, this subsystem generates a path towards the target, and tracks the path.

2.3 Stanford University—Junior

The Stanford University's research team on intelligent vehicles has been one of the most experienced and successful research labs in the world. To better study and promote the applications of autonomous intelligent vehicles, the Volkswagen group founded the Volkswagen Automotive Innovation Laboratory (VAIL). Until now, Stanford University collaborated with the Volkswagen Group and built several intelligent vehicles, the Stanley (the autonomous Volkswagen Touareg that won the DARPA Grand Challenge in 2005 [10]), Junior (the autonomous Volkswagen Passat that was the runner-up in 2007 DARPA Urban Challenge [14]). Moreover, Google has licensed the sensing technology from Stanley to map out 3D digital cities all over the world. We will introduce Junior that participated in the 2007 Urban Challenge below.

Junior [14], shown in Fig. 2.2, is a modified 2006 Volkswagen Passat wagon, equipped with five laser range finders, a GPS/INS, five radars, two Intel quad core computer systems, and a custom drive-by-wire interface. Hence, this vehicle is capable of detecting an obstacle up to 120 m away.

Junior's software architecture is designed as a data-driven pipeline and consists of five modules:

- Sensor interface: This interface provides data for other modules.
- Perception modules: These modules segment sensor data into moving vehicles and static obstacles, and also provide accurate position relative to the digital map of the environment.
- Navigation modules: These modules consist of motion planners, a hierarchical finite state machine, and generate the behavior of the vehicle.
- Drive-by-wire interface: This interface receives the control commands from navigation modules, and enables the control of throttles, brakes, steering wheels, gear shifting, turn signals, and emergency brake.
- Global services: The system can provide logging, time stamping, message-passing support, and watch-dog functions to keep the system running reliably.

Furthermore, we introduce three fundamental modules: environment perception, precision localization, and navigation. In the perception module, there are two basic functions, static/dynamic obstacle detection and tracking, RNDF localization and update, where lasers implement primary scanning, and a radar system works as an early warning for moving objects in intersections as complement. After perceiving traffic environment, Junior estimates a local alignment between a digital map in the RNDF form and its current position from local sensors. In navigation module, the first task is to plan global paths, where there are two navigation cases, road navigation and free-style navigation. However, basic navigation modules do not include intersections. Furthermore, Junior strives to prevent itself from getting stuck in behavior hierarchy.

Nowadays, researchers at Stanford University are still working on autonomous parking in tight parking spots[1] and autonomous valet parking.

2.4 Virginia Polytechnic Institute and State University—Odin

The team VictorTango formed by Virginia Tech and TORC Technologies developed Odin[2] [2], which took the third place in 2004 DARPA Grand Challenge. The Odin consists of three main parts: base vehicle body, perception, and planning.

Now, we introduce the base vehicle platform. Odin is a modified 2005 Hybrid Ford Escape, shown in Fig. 2.3. Its main computing platform is a pair of HP servers, each with two quad-core processors.

In the perception module, there are three submodules: object classification, localization, and road detection. Here, object classification first detects obstacles and then classifies them as either static or dynamic. The localization submodule yields the vehicle position and direction in the 3D world. The road detection submodule extracts a road coverage map and lane position.

The planning module uses a Hybrid Deliberative-Reactive model, which consists of upper level decisions and lower level reactions as separate components. The

[1] http://cs.stanford.edu/group/roadrunner/.

[2] http://www.me.vt.edu/urbanchallenge/.

Fig. 2.3 The intelligent vehicle Odin developed by the Team VictorTango (published courtesy of Virginia Polytechnic Institute and State University)

coarsest level of planning is the route planner responsible for road segments and zones the vehicle should travel in. The driving behavior component takes care of obeying road rules. Motion planning is in charge of translating control commands into actuator control signals.

2.5 Massachusetts Institute of Technology—Talos

Team MIT has developed an urban autonomous vehicle, called Talos[3] (shown in Fig. 2.4) [1, 9, 13]. There are three key novel features: (i) perception-based navigation strategy; (ii) a unified planning and control architecture; (iii) a powerful new software infrastructure. Moreover, this vehicle consists of various submodules: Road Paint Detector, Navigator, Lane Tracker, Driveability Map, Obstacle Detector, Motion Planner, Fast Vehicle Detector, Controller, Positioning Modules. The perception module includes obstacle detector, hazard detector and lane tracking submodules. Planning a control algorithm involves using a navigator, driveability map, motion planner, and a controller. The navigator plays an important role in mission-level behavior, and the rest of these submodules work together in a tight coupling to yield the desired motion control goal in complex driving conditions.

[3] http://grandchallenge.mit.edu/.

Fig. 2.4 The intelligent vehicle Talos developed by the Team MIT (published courtesy of Massachusetts Institute of Technology)

Fig. 2.5 The intelligent vehicle Skynet developed by Team Cornell (published courtesy of Cornell University)

2.6 Cornell University—Skynet

Team Cornell's Skynet[4] is a modified Chevrolet Tahoe, shown in Fig. 2.5, and consists of two groups of sensors [15]. One group is used for sensing vehicle itself, and the other group (laser, radar and vision) is for sensing the environment. Thanks to the above sensors, Skynet is capable of providing real-time position, velocity, and

[4] http://www.cornellracing.com/.

attitude for absolute positioning. Moreover, Skynet's local map including obstacle detection information is the map of local environment surrounding Skynet. In many cases, autonomous driving in complex scenes is more than basic obstacle avoidance. Hence, the vehicle-centric local map is not enough for absolute positioning. We need to estimate environment structures using posterior pose and track generator algorithms.

Skynet is using the probabilistic representation of the environment to plan mission paths within the context of the rule-based road network. One intelligent planner includes three primary layers: a behavioral layer, a tactical layer, and a operational layer. The goal of the behavior layer is to determine the fastest route to the next mission point. When there exist state transitions in the behavior layer, the corresponding component of the tactical layer is executed. Among the four tactical components, the road tactical component is to seek a proper lane and to monitor other agents in the same and neighboring lanes. The intersection tactical component handles intersection queuing behavior and safe merging. The zone tactical component takes care of basic navigation in unconstrained cases. The blockage tactical component implements obstacle detection and judging whether there are temporary traffic jams, and acts accordingly. The final layer is an operational layer which is in charge of converting local driving boundaries and a reference speed into actuators, steering wheels, throttles, and brakes.

2.7 University of Pennsylvania and Lehigh University—Little Ben

Little Ben[5] designed by the Ben Franklin Racing Team is a modified Toyota Prius with various sensors and computers for the 2007 DARPA Urban Challenge [4], shown in Fig. 2.6. Similar to other intelligent vehicles, Little Ben is equipped with various sensors, such as three LMS291, two SICK LDRS, and a Bumble bee stereo camera. The sensor array provides timely information about the surrounding environment, which is integrated into a dynamic map for environment perception and modeling.

Little Ben's software framework consists of perception, planning, and control. Its perception module is responsible for providing static obstacles, moving vehicles, lane markings, and traversable ground. Little Ben's primary medium-to-long-range lidars are responsible for geometric obstacles and ground classification, road making extraction, and dynamic obstacle tracking. Moreover, the stereo vision system is used to detect close road makings. Once the perception module generates information about static obstacles, dynamic obstacles, and lane markings, the MapPlan module will update obstacles and lane marking likelihoods in a map centered at the current vehicle location. The mission and path planning consists of two stages. The first stage is to calculate the optional path by minimizing the mission time. The next

[5] http://benfranklinracingteam.org/.

Fig. 2.6 The intelligent vehicle Little Ben (published courtesy of the University of Pennsylvania and Lehigh University)

stage is to incorporate the dynamic map into new path planning. Afterwards, the path follower module is responsible for calculating the vehicle steering and throttle-brake commands to follow the desired trajectory.

2.8 Oshkosh Truck Corporation—TerraMax

The TerraMax Vehicle[6] is a joint effort by Oshkosh Truck Corp., Rockwell Collins, and the University of Parma [5], and is shown in Fig. 2.7. In this vehicle, Rockwell Collins was in charge of the intelligent vehicle management system. Oshkosh Truck Corporation was working on project organization, system integration, low level control hardware, modeling and simulation support, and the vehicle, while the University of Parma provided the vision module. The most important feature is that this vehicle has big size (weighs around 30000 pounds, is 27 feet long, 8 feet wide, and 8 feet high), so it has to travel slowly.

Considering dynamic analysis of its mechanical systems, TerraMax provides underbody, steer angles, and lateral stability information for control modules. The full vehicle model consists of suspensions, steering, chassis, and tires. A typical simulation method over 70 different obstacles is used to evaluate the underbody clearance, for better handling of different obstacles at low speeds. The steering simulation is used to allocate both the front and rear steering angles, when given a steering wheel input. In addition, constant-radius tests were used to evaluate the lateral stability of the truck.

The intelligent Vehicle Management system (iVMS) developed by the Rockwell Collins is an interface between the vehicle systems and onboard sensors. Moreover,

[6] http://en.wikipedia.org/wiki/TerraMax_(vehicle).

Fig. 2.7 The intelligent vehicle TerraMax (published courtesy of the Oshkosh Truck Corporation)

the iVMS provides various autonomous functions, such as vehicle control, real time path planning, obstacle detection, behavior management, and navigation.

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