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Introduction

This chapter provides an introduction to the whole book. After a section on motivation and introduction, a brief history of automated driving is presented, followed by how Advanced Driver Assistance Systems (ADAS) naturally evolved into autonomous driving functions. Some past and current autonomous driving architectures are presented using examples from the field. A literature review section where the key papers and more recent developments in path planning and robust path-tracking control for autonomous road vehicles, also including the relevant literature on cybersecurity, and how it relates to autonomous vehicle path planning and tracking, are summarized next. This is followed by a section on the scope of the book, briefly detailing what is covered in each chapter. The chapter ends with a brief summary and concluding remarks.

1.1 Motivation and Introduction

The race toward series produced autonomous road vehicles has been rapidly progressing during the last decade. Most automotive OEMs and technology companies had promised or forecasted autonomous driving models by the year 2020, two years before the publication date of this book. This obviously did not take place. While we do not have truly autonomous driving vehicles that the public can currently buy, the currently available lane keeping, adaptive cruise control (ACC), emergency braking systems, traffic jam assistants, and their extended versions in some vehicles allow an almost autonomous highway driving experience under ideal conditions [1]. Autonomous shuttle service has been successfully deployed in a lot of different geofenced areas worldwide [2–4]. Large-scale autonomous taxi service is about to start in several countries in Asia soon, using drive-by-wire vehicles retrofitted with sensors and control systems [5]. Autonomous vehicle races have also been increasing around the world [6]. Autonomous delivery vehicles and autonomous truck platoons are also technologies with many successful, limited-scale deployments [7, 8]. Automotive OEMs were planning to introduce autonomous products for the fleet market first, before making them available to the general public. Introduction of autonomous vehicle fleets that can also be used as ride hailed taxis is now expected by the year 2023 even though there may still be delays considering the failed predictions of the recent past. The current technology of traditional and nontraditional automotive OEMs and technology companies like Google's Waymo, and similar ones is sufficiently advanced for nearly full driverless operation in well-mapped environments under ideal conditions. The relatively smaller percentage of nonideal conditions and uncertain environments make it difficult to implement full-scale autonomous driving under arbitrary conditions and environments.

Autonomous Road Vehicle Path Planning and Tracking Control, First Edition.
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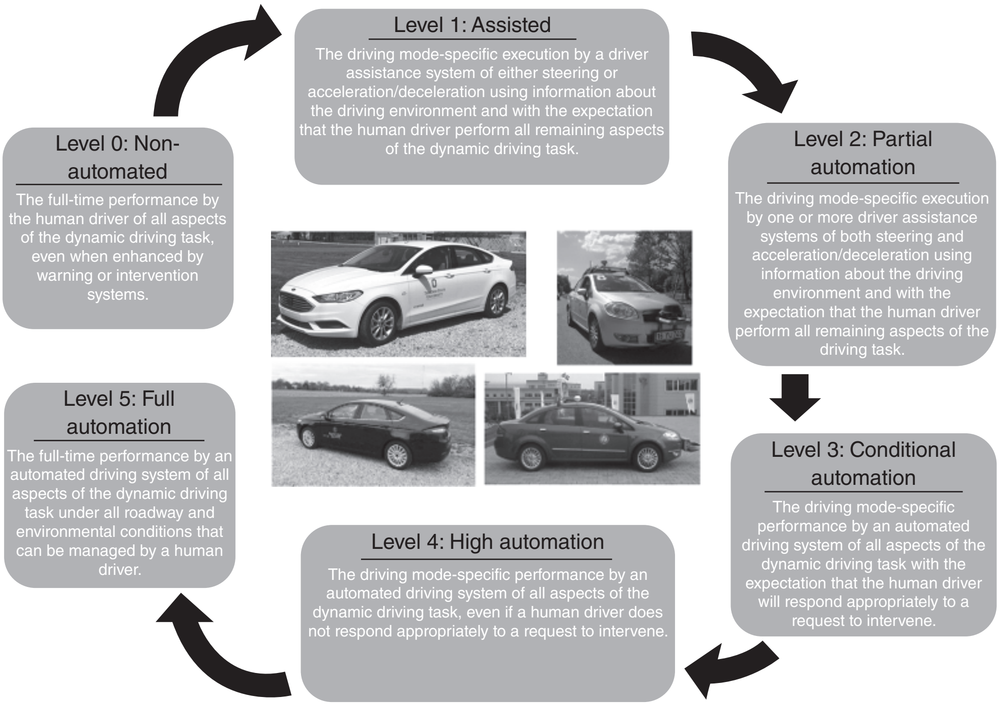

Level 0: Non-automated

The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems.

Level 1: Assisted

The driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task.

Level 2: Partial automation

The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the driving task.

Level 3: Conditional automation

The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene.

Level 4: High automation

The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene.

Level 5: Full automation

The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.

Figure 1.1 Categories of autonomous driving according to SAE.

Autonomous road vehicles have been categorized into six categories by the Society of Automotive Engineers (SAE) as shown in Figure 1.1 [9]. Currently available automated driving technology in series produced vehicles falls under Level 2 which is partial automation. Level 2 partial automation is achieved in series production vehicles with lane-centering control for steering automation and ACC and collision avoidance for automation in the longitudinal direction. L3 partial automation is characterized by all driving actuators being automated and the presence of a driver who can intervene when necessary. Recently introduced autopilot systems for cars are examples of conditional automation where the car takes care of driving in some driving modes like highway driving but the human operator is always in the driver seat to take over control if necessary. The Highway Chauffeur is a Level 3 autonomous highway driving system in which almost all highway driving functions are carried out autonomously, but the driver is needed to take over if something goes wrong or might go wrong like a lane change maneuver [10]. The Highway Chauffeur is currently available technology for series produced vehicles and uses an eHorizon electronic map to take care of driving on the highway until the chosen exit is reached. The Highway Pilot is a Level 4 autonomous driving extension of the Highway Chauffeur [11]. The driver is still in the driver's seat but the vehicle can perform highway driving completely autonomously without the need for driver interaction. Highway Pilots are expected to enter the market after 2022 [12].

In Level 5 driving automation, there is no need for a driver as the vehicle takes care of all driving tasks autonomously. It is clear that SAE Level 4 and Level 5 autonomous vehicles have to be capable of making their own decisions based on situational awareness using perception sensors and decision-making algorithms to satisfy the fixed mission of following the highway between initial and final destination locations. This includes planning their route once the destination point is specified and taking care of path planning, path-tracking control, and collision avoidance maneuvering, if needed, autonomously. This same approach is also needed for the lower speed autonomous driving in urban city environments which is a much more complicated situation due to the many other actors like vulnerable road users being present and more unexpected situations being likely to occur. This book treats path planning, path tracking control, and collision avoidance maneuvering for both urban and highway autonomous driving and also treats pedestrian collision avoidance of autonomous driving in the context of the urban application.

Automated driving shuttles in smart cities that are used for solving the first-mile and last-mile problem are other well-known, emerging examples of autonomous road vehicles [11]. These shuttles operate at relatively lower speeds which definitely improves safety levels while also creating a traffic bottleneck around them. In comparison to limited access highway operation, these shuttles operate in significantly less-structured environments with unpredictable interaction with vulnerable road users such as pedestrians, bicyclists, and scooters. The roads they use involve pedestrian crosswalks, intersections with or without traffic lights, roundabouts, and sharper turns as lower speed of operation is possible. Successful applications of these low-speed autonomous shuttles exist in fixed routes. The whole route needs to be mapped in advance and extra landmarks in the form of signage have to be added in some cases as scan matching of the recorded map is used for localization of these autonomous shuttles. Level 4 like autonomous driving of these shuttles is achieved during the segments of the route without intersections and unexpected interactions with other road users. The safety driver takes over control of the vehicle in intersections and during unexpected events. This is called assisted autonomy and is currently necessary for safe operation. True Level 4 autonomous driving capability of these low-speed urban environment autonomous vehicles is expected to be realized in the near future.

The most fundamental task of an autonomous vehicle is the ability to plan and follow a path while avoiding collisions. Path planning is optimized to make sure that the resulting trajectories have comfortable motion with limited acceleration and jerk. Uncertainties in environmental conditions, vehicle dynamics, vehicle load, and load distribution and the range of required speed from very low speeds for urban driving to highway driving speeds require the path tracking and collision mitigation controls to be robust. The motivation of this book is to contribute to this very important area of autonomous driving by presenting recent research results in path planning and robust path-tracking control. Robustness is achieved through two different approaches. The first one is regulation of the path following dynamic model to reject the uncertainties and disturbances and to handle the variable time delays that are present. The second approach is to use a robust feedforward and feedback controller combination to achieve guaranteed performance. The presence of static or moving obstacles such as other cars, pedestrians, and bicyclists is also treated by presenting methods for modifying the path to avoid such collisions in realistic applications. The methods presented in the book are applicable in real life, having been tested in a realistic hardware-in-the-loop simulation environment and in road testing with a research-level autonomous vehicle in addition to the usual model-in-the-loop simulations.

1.2 History of Automated Driving

Contrary to popular belief, the origins of autonomous driving and automated vehicles go back all the way to the 1920s. Radio-controlled cars were the novelty in the 1920s while 1960s and 1970s saw the emergence of cable-controlled cars, actually and unknowingly taking a step backwards. Computer-controlled cars resembling today's autonomous vehicles started emerging in a very rough form in the 1980s and 1990s. In the first driverless car experiments of the 1920s, an antenna was mounted on the car which was driven by an external operator using radio signals, much like radio-controlled toys. It should be noted that this remote operation forms the basis of some current driverless vehicles being followed by a second vehicle whose operators can take over control and intervene, if necessary. The presence of a safety operator, whether in a nearby other vehicle or in the driver's seat, is one of the current major limitations of autonomous driving. The car in the 1920s example obviously had to be in the field of vision of the external operator and also had to be operated at low speeds. A totally different approach was taken starting in the 1960s to get rid of the safety driver. Cables carrying electricity and generating a magnetic field were embedded in the roads. A downward-looking magnetic pickup in the car was used to follow this magnetic field much like the way toy cars follow reflective tape fixed on the ground. This approach obviously did not work in the long run due to the tremendous work and cost required for the necessary road infrastructure. The first computer-controlled cars that were developed later used camera and later also radar to do lane keeping and speed alterations much like today's lane-centering and ACC systems to automatically follow roads and cars. The computational power available was very limited as compared to what is available now with our robust operating systems and our fast CPUs and GPUs with large memory and storage capability.

The first documented radio controlled car was produced in 1925 by Houdina Radio Control, a radio equipment firm. The car called the Linrrican Wonder traveled through a traffic jam in New York City and was controlled by a transmitting antenna. The car behind this “phantom auto” sent signals to the antenna, and the signals worked on small electric motors that actuated the necessary pedals and steering. The Linrrican Wonder was obviously also a drive-by-wire vehicle. It was driverless in that the driver was in the following vehicle. The actuator positions of this following vehicle were mimicked by the driverless vehicle in a master–slave configuration. This is similar to the master–slave configuration that is used in some platooning applications with the difference that the master is the following vehicle and not the lead one which will obviously introduce unnecessary phase lag to the coupled system due to the communication time delay involved and this delay will destabilize the system at higher speeds. Nevertheless, this radio-controlled phantom lead car followed by the second control signal-generating car is an early example of automated platooning. The control signals rather than vehicle acceleration are sent to the next vehicle as is proposed in the recent connected cruise control (CC) concept. The human operator in the following car also acts like a cloud computer that computes and relays the necessary control commands to the driverless lead car. This radio-controlled driverless car is illustrated in Figure 1.2. Note that a similar procedure of having a second car with operators follow a truly driverless car with passengers was used recently for safety purposes [13]. This radio-controlled driverless vehicle concept from the 1920s also has similarities to the currently used phantom driver concept which is used to remotely operate a truly driverless vehicle in emergency situations that the autonomous driving system cannot handle [14]. The remote operator has full access to the sensor data and surround view from

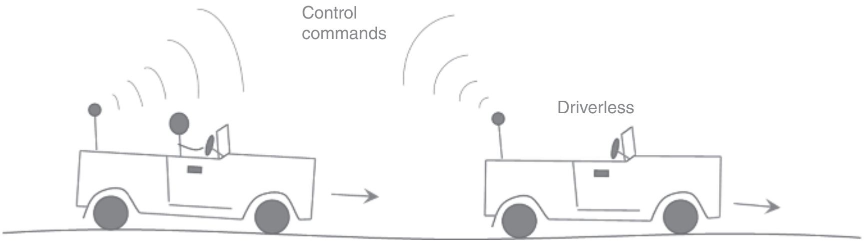

Figure 1.2 Illustration of radio-controlled driverless car of 1920s.

the driverless car and can operate the car using his/her steering and pedal inputs like manual driving. The variable communication delays involved create possible stability problems that need to be handled just like those that occur in telemanipulation. These delays are expected to become much smaller in magnitude with 6G communication which is the driving point behind current collaborative perception and awareness systems.

There have also been successful proof-of-concept type implementations of Intelligent Transportation Systems (ITSs) technology dating back to 1925. Charles Adler was named the man who invented Intelligent Traffic Control a century too early [15]. He embedded magnetic plates in the road at a point before the road led into a sharp curve. He also prepared a car with a speed governor that would be activated as the car drove over the magnetic plate such that the vehicle engine would be commanded to slow down to 24 km/h. This is a very early hardware implementation of Curve Speed Warning [16] and automatic speed reduction system where the whole system has been implemented as a hardware solution.

The General Motors *Futurama* exhibit at the 1939 World's Fair in New York is viewed by many as the first large-scale ITS and highway automation concept and vision [17]. The vision of *Superhighways* was demonstrated in this exhibit where the visitors would sit and watch a scaled down replica of a future city complete with highways and guided cars. This was a hard 3D model version of the current game engine rendered environments with traffic cosimulation [3, 18–21]. These guided cars were navigated automatically using radio control and could enter curves at speeds up to 50 mph (80 km/h). This vision of Superhighways was presented as what would happen in 1960. In compliance with this idea, there was a desire in the automotive industry to have cable buried in lane centerlines in these envisioned superhighways to create a magnetic field that could be followed automatically by self-driving vehicles. This approach was not adopted because of higher initial cost and higher maintenance cost during repairs. This vision was one of self-driving based on infrastructure which is exactly why it failed.

The current infrastructure-based technology that can be used for following lane centerlines is the use of a front-looking camera to detect and track the lanes in a lane-keeping assistance system. The problem with this technology is that the lanes cannot be detected when weather conditions degrade the camera performance or when the road is covered with snow, making the lanes invisible. Since the interstate roads were built without voltage carrying cable buried inside, automotive OEMs lost interest in self-driving as the required infrastructure was not there. Researchers and some states like California continued on with this Superhighway idea, which changed its name to Automated Highway Systems, until the 1990s, but while there were a lot of successful demonstrations and a large literature of research results, larger-scale use of this technology never happened as automotive companies did not want to develop cars dependent on nonexisting and costly infrastructure and as there was also no demand from car buyers. Nevertheless, different ways of embedding passive signals to be followed inside roads continued until recent years in the form of equally spaced metallic pins, reflective tape, and more recently smart paint [22, 23]. Out of these, smart paint uses nanoparticles embedded inside normal paint used in lane markings and can be detected with a simple sensor. It can also be detected if the road is covered with snow and offers a relatively cheap and highly accurate way of localization in campus like environments or geofenced urban areas for low-speed autonomous driving applications as the preview distance is constrained to be small.

According to reference [24], the first self-driving car was built and tested by the Radio Corporation of America (RCA) in 1957 on a 400 ft public highway in Lincoln, Nebraska. The steering wheel and pedals in this vehicle were replaced with a small joystick and an emergency brake while the vehicle speed and distance with the car in front were displayed on the dashboard. Self-driving was activated by pressing the Electronic Drive button and the car would follow its lane and adjust its speed automatically. RCA was working on this technology around the 1950s. During the same time frame around 1956, GM shared its vision of a futuristic car driving autonomously in an automated highway using a professional video in the Motorama auto show. Automated highway driving involved a control center directing traffic much like today's aircraft traffic control centers.

According to Wetmore [25] GM and RCA developed a scaled version of an automated highway system by 1953. They used this scaled automated highway system to investigate how electronics can be used for path-tracking and car following. Note that this is very similar to the scaled drive-by-wire vehicles with sensors like the F1TENTH vehicles [26, 27] that a lot of academic research groups use for in-the-lab studies of autonomous driving and decision-making. In 1958, GM built a prototype self-driving vehicle with a pickup in front that would sense the alternating current of a wire embedded in the road [25]. This was used for localization with respect to the path to be followed and for generating the required corrective steering action. The research vehicle could take turns automatically without driver steering intervention. By 1960, GM had tested its research vehicles in test tracks with automatic path-tracking, lane-change maneuvering, and car following. Since the technology used was based on cable and signals buried under the road, these research efforts stopped after the interstates were built without this infrastructure required for automated highways.

The first university based self-driving studies started around the 1960s just as the industry studies were ending. The same technology of a live wire either buried in the road or fixed on top of the road was used to steer a vehicle in a closed test area as shown in Figure 1.3 by Ohio State University researchers [28]. An analog computer was used to implement steering control and speed control as shown in Figure 1.4. This vehicle was converted into a drive-by-wire one and the analog joystick shown in Figure 1.5 was developed and used in the car for operator intervention. Turning the handle of the joystick left or right was used for steering in the same direction. Moving the joystick handle forward applied throttle while moving it backwards applied braking. In later years, longitudinal car following was implemented by actually connecting the two cars by wire and communicating the necessary information like distance and speed difference through this hard wire. Connected vehicles (CVs) actually meant being physically connected during 1960s. As compared to today's wireless networked car following systems, this wired and truly connected version obviously did not have the wireless communication delays that limit the minimum achievable time gaps of present platooning systems and cooperative ACC.

While the historical self-driving car work presented until this point focused on automating the longitudinal and lateral motions of the on-road vehicle, its controls, some very basic radar perception and road-fixed cable based localization; work on autonomy or intelligence, i.e. decision-making, was not being pursued owing mostly to the structured nature of highway driving. On the other hand, the mobile robotics community was using low-speed mobile robots with simple mechanical designs to use camera sensors for perception of the environment and

Figure 1.3 First university based self-driving study by Ohio State University researchers. Source: Fenton and Olson [28]/with permission from IEEE.

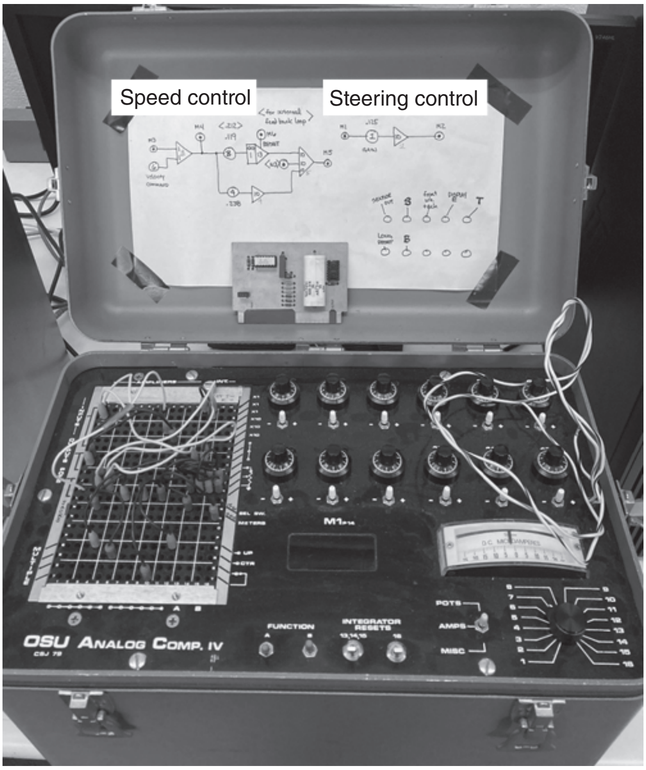

Figure 1.4 Analog steering and speed control of 1960s Ohio State University self-driving vehicle. Source: The Ohio State University.

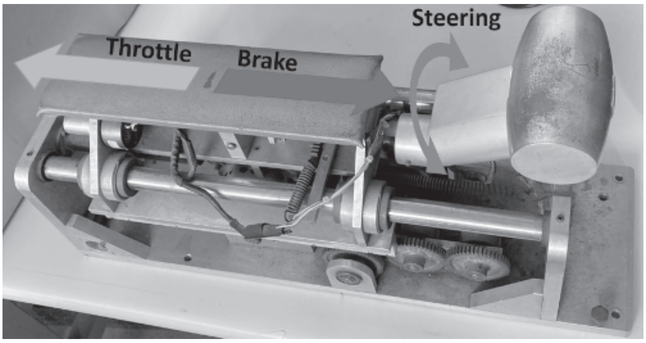

Figure 1.5 Joystick for drive-by-wire interface of Ohio State University self-driving vehicle from the 1960s. Source: The Ohio State University.

scene understanding to be used in decision-making for autonomously navigating through previously unknown obstacles by planning and executing a collision free path. Unlike the highway driving application, these mobile robot studies were geared toward rovers to operate in the moon and much later in Mars and, thus, required a high level of autonomy in a highly unstructured and uncertain off-road environment. The requirement of remote control of these mobile robots from earth also introduced considerable time delay on the order of 2.5 seconds for the shortest tele-distance example into their feedback control loop. The Stanford cart was the first prototype of these mobile robots introduced in 1961 [29]. Much work was done using this research platform and its extensions in the 1970s. The Stanford Cart used cameras to detect and follow a solid white line on the ground which is similar to the vehicles following a live cable buried inside the road.

The Stanford Cart was followed by the Artificial Intelligence Center of Stanford Research Institute's (SRI) mobile robot called Shakey. The Cart and Shakey were the first mobile robots and also the first self-driving vehicles that used digital computers instead of electronics and analog computers. These computers were like the cloud computers of today as they were using very large mainframe computers through radio links. Both the Cart and Shakey used cameras to perceive the environment as compared to magnetic field pickup sensors and radar being used by their on-road vehicle counterparts of the same timeframe. The Cart was able to follow white lines and Shakey used image processing to detect large prismatic objects. The mechanical structure of Shakey looked a lot like the mobile robots of today. Current mobile robots, of course, have very high-embedded computational power and use three-dimensional lidar along with cameras. They also have relatively high accuracy global positioning system (GPS) and inertial measurement unit (IMU). The image processing and decision-making algorithm development approach of the mobile robotics approach and the highway ready vehicle platforms, motion controls, and radar sensors of the on-road self-driving approach united in an evolutionary manner in the decades to follow the 1970s to form the basis of current autonomous driving vehicles with the peak results being achieved in the DARPA Challenges of 2000s.

A rough combination of both approaches resulted in the autonomous vehicle of Japan's Tsukuba Mechanical Engineering Laboratory. This vehicle that looked like a large multiwheeled mobile robot with an armored-vehicle like body shell first used two cameras for perception of white lines on the road. Analog computers were used for signal processing as digital computers were still too large to fit inside the vehicle. The car was able to reach speeds of to 30 km/h (18.6 mph) which is close to the 25 mph speed limit of current autonomous shuttles used in urban areas. The digital computer problem was solved in the late 1980s as they were able to fit within a van. In Germany, in the beginning of the 1980s, a Mercedes-Benz van with cameras and other sensors used a digital computer for self-driving control [30]. In 1986, another vehicle named VaMoRs from the same group drove by itself with speeds up to 96 km/h. being achieved in 1987. It is clear that the ability to use digital computers and use of in-vehicle sensors instead of infrastructure-based sensing sparked the interest of automotive companies in self-driving vehicles again.

During 1987 to 1995, the European Union funded the Prometheus (PROgraMme for a European Traffic of Highest Efficiency and Unprecedented Safety) project led by major European automotive OEMs and research organizations [31]. A 1758 km self-driving trip from Munich, Germany, to Copenhagen, Denmark, and back was the end result of this large scale and very high budget project. In 1994, the project demonstrated in Paris: Vision Enhancement, Friction Monitoring and Vehicle Dynamics, Lane Keeping Support, Visibility Range Monitoring, Driver Status Monitoring, Collision Avoidance, Cooperative Driving, Autonomous Intelligent Cruise Control, Automatic Emergency Call, Fleet Management, Dual Mode Route Guidance, Travel and Traffic Information Systems. These are all parts of a Highly Automated Driving (HAD) system. The Paris demo in 1994 also involved the twin automated vehicles VaMP and VITA-2 self-driving for more than 1000 km on a multiple lane highway in traffic at speeds up to 130 km/h. Self-driving included lane keeping, car following of the two automated vehicles, and lane changes for overtake maneuvers.

The situation in the United States was much different than the one in Europe as automotive OEMs had lost interest in self-driving technology. During 1980s, the research work at the Ohio State University ended due to lack of funding. Starting around 1986 and continuing until present, the California Partners for Advanced Transit and Highways (PATH) carried out research on automated highway systems first and on ITS in later years. PATH is a collaboration between the California Department of Transportation (Caltrans), UC Berkeley, other public and private academic institutions and private industry. While the PATH program was well funded and was very successful in the deployment of intelligent vehicle technologies such as convoy driving, merging, leaving convoys, it suffered from not being backed up by automotive OEMs. As a result, some early ideas failed and the research results were not adopted by the automotive industry until much later. In 1995, two researchers from Carnegie Mellon University's Robotics Institute used a minivan they called NavLab 5 to drive autonomously in a 2850 mi trip from Pittsburgh to San Diego [32, 33]. Their self-driving system called Rapidly Adapting Lateral Position Handler (RALPH) was a camera-based system and did 98% of the driving. The technology had been developed in CMU's Robotics Institute since 1986. NavLab 5 used a desktop-like computer, a camera, a GPS sensor and a high accuracy fiber-optic gyro sensor. NavLab 5 had lane keeping, automatic lane changing, blind spot monitoring and decision making capabilities. Two years later, the demonstration called Demo'97 was organized by the National Highway Systems Consortium (NHSC) in 1997 with participants invited from research organizations, universities, and automotive manufacturers and suppliers [34]. Separate, special purpose lanes in a highway in California were closed for the demo which mainly consisted of platooning and related technologies to demonstrate the efficacy of Automated Highway Systems. Within the same timeframe in 1994, a computer vision lab called VisLab in Italy developed a self-driving vehicle they called ARGO [35]. The camera-based self-driving capability of ARGO was tested for more that 2000 km on Italian highways with regular traffic, and ARGO was in self-driving mode 94% of the time during this deployment.

The 2000s were a revolutionary timeframe for autonomous vehicles with the DARPA autonomous driving challenges taking place. The DARPA Grand Challenges took place in the Mojave Desert in the United States during 2004 and 2005 [36, 37]. The route was 241 km alongside Interstate 15. The first DARPA Grand Challenge in 2004 was not successful as none of the autonomous vehicles were able to finish it. The longest distance traveled was 11.78 km by the Red Team from CMU Robotics Institute [38]. There was a qualifying round at the California Speedway test course at Fontana, California, where the teams showed their vehicle and approach to the judges to be selected for the actual event. The actual route, out of many possible choices and GPS waypoints to be followed, was given to the teams shortly before the challenge so that they could not create a route specific solution in advance. The waypoints that were given to the teams were so dense that a path planning algorithm was not even needed, considering also the necessity of using lower speeds because of the off-road like terrain. Fifteen vehicles were allowed to take part in the 2004 challenge but two of them had to be withdrawn before the event. The challenge was scheduled to run for ten hours but only four of the participant vehicles were operational after the first three hours. Most vehicles had mechanical failures or GPS problems. Some of them were stopped by the judges as their algorithms got stuck. The Red Team vehicle that went furthest also went off course at the end and got stuck in an embankment. While the 2004 DARPA Grand Challenge was not successful operationally, there were a lot of lessons learned and a lot of collected data to work with.

When the challenge was repeated in 2005, the new off road course was 212 km long [39]. Except for one team, all of the 23 finalists were able to go beyond the 11.78 km maximum distance traveled in the 2004 event autonomously. Four of the autonomous vehicles completed the course on time while a fifth one, a large truck, finished over the ten-hour limit. The 2005 route had three narrow tunnels and 100 high curvature turns as compared to the wider and less curved route of the 2004 challenge. Stanley from Stanford University was the winner of the 2005 DARPA Grand Challenge [40]. The Grand Challenges were followed in 2007 by the DARPA Urban Challenge that took place in an Air Force base in California [41]. The course was 96 km long, representative of an urban driving environment and had to be completed within six hours. There were manually driven vehicles with professional drivers who circulated parts of the route to re-create the urban driving environment. DARPA organized the teams into two tracks and provided $1 M funding to teams in Track A most of which teamed up with automotive OEMs and technology companies. Not all of the teams were invited to the finals based on their semifinal performance. Tartan Racing's (CMU) Boss finished in first place, followed by Stanford Racing's Junior [42, 43]. Only six teams were able to finish the whole course and out of those only four teams were able to finish in time. The average speed of the first three teams was about 13–14 mph which is similar to the speeds of current autonomous shuttles operating in urban environments. The Massachusetts Institute of Technology (MIT) and Cornell teams had their famous autonomous vehicle (AV) accident in this event, but they were both able to finish the challenge, nevertheless [44]. In the DARPA Grand Challenges, all teams had similar sensor, computational system and software configurations with the gap, increasing in favor of the winning teams in the 2005 challenge. The difference in sensor, computational platform and AV software between the winning teams and the others showed a major gap in the Urban Challenge where some of the winning teams had developed perception, detection/tracking, planning, path-tracking, and visualization routines similar to the ones used today which gave them a significant advantage.

The 2007 DARPA Urban Challenge and the subsequent interest and work of Google using the developed technology for recording images and building maps more efficiently have laid the framework for today's autonomous driving technology. The low-speed, self-driving vehicles that Google developed and used for map-building purposes had a very strong impact on the public image of AV technology. Even though automotive OEMs, suppliers, research centers, and universities had already significantly developed autonomous driving technology, vehicle owners had not shown a big enthusiasm for and interest in technology. Very interestingly, the successful implementation of existing AV driving methods by a search engine company was more impactful in making people believe that AV technology is for real and works. With public acceptance, belief, and expectation, autonomous driving has since seen extensive research and development investments.

Successful deployments of AV technology continued after the DARPA Urban Challenge of 2007. A significant one of these deployments was the VisLab Intercontinental Autonomous Challenge funded by the European Union. A convoy of vehicles, two of them being AVs that follow each other, started from Parma, Italy in 2010 and drove semiautonomously all the way to Shanghai, China [45]. The first vehicle in the convoy was driving semiautonomously while the second vehicle followed it autonomously. They were followed by other vehicles used for support and maintenance. The 2013 autonomous drive on the Bertha Benz Memorial Route was an example of another successful autonomous driving deployment after the DARPA challenges. The course taken by the autonomous vehicle was 103 km long that included both rural roads and major cities with a large variety of difficult traffic scenarios including intersections with and without traffic lights, roundabouts, and narrow passages with oncoming traffic [46].

On the cooperative autonomous driving side, the Grand Cooperative Driving Challenge (GCDC) took place in 2011 in Helmond, Netherlands, on a closed highway segment where eight different teams ran multiple heats of cooperative driving with autonomy in the longitudinal direction [47]. While cooperative driving deployments had taken place before, this was the first one where the two side-by-side platoons had vehicles from different teams that used different vehicles ranging from a Smart to trucks. The convoys had different vehicle pairings in each heat and drove autonomously (longitudinally) and cooperatively while performing convoy merging, handling traffic lights and responding to speed limits autonomously, using IEEE 802.11p DSRC V2X communication. As the number of autonomous vehicles on public roads increases, they will have to communicate with each other, with the infrastructure and driving in a coordinated fashion. The GCDC 2011 was repeated in 2016 with both longitudinal and lateral autonomy. After only a decade since the GCDC 2011, DSRC technology for V2X communication is being replaced by cellular communication. Truck platooning and automated-driving trucks are applications of this technology that are currently being used on public roads.

More recent deployments of AV and Connected Vehicles (CVs) technology are too many to report. Of interest is the Roborace since it is a truly driverless race in which all teams use the same vehicle and hardware and software platforms, making it a race between different AV driving algorithms. The 2016 Smart City Challenge in the United States is also an interesting recent example of many AV/CV deployments that recently ended in Columbus, Ohio, as the Smart Columbus project [3]. AV shuttles were successfully operated in two different urban environments in Smart Columbus and more than 100 traffic lights and about 1500 vehicles were fitted with road-side units (RSUs) and on-board units (OBUs), respectively, with collected data being available on a cloud server.

1.3 ADAS to Autonomous Driving

The continuity of developments in active safety systems and ADAS in the automotive area have resulted in the basis of current HAD and Automated Driving technologies that are gradually being introduced to series-produced road vehicles. The earliest active safety system is anti-lock brakes (ABS) that prevent locking of wheels during sudden braking especially on slippery surfaces while also aiming to keep steerability. This is a very important feature for obstacle avoidance systems in path-tracking control of autonomous vehicles. Traction control systems (TCSs) work in the opposite direction of wheel slip and aim at avoiding spinning of the wheels during sudden applications of driving torque, again especially on slippery road conditions. ABS focuses on all wheels of the vehicle by individually braking them for optimizing slip while TCS applies individual wheel braking to just the drive wheels along with drive torque reduction. Electronic stability control uses the same hardware to reduce drive torque and brake wheels individually to reduce speed and apply steer-by-braking to regulate the yaw rate of the vehicle to correspond to the driver applied steering. ABS/TCS/ESC is currently available as a bundle in current cars and ABS and ESC are mandatory. While TCS is not mandatory, it is always present since it is very easy to implement once ABS and ESC are present and since customers demand its presence. While braking-based ESC was explained here, steering-based ESC is also possible with a combination of individual wheel braking and steering giving best results [48].

Years of development of ABS/TCS/ESC systems have resulted in the possibility of easily implementing automated braking and throttle systems in current vehicles for longitudinal automation of motion. Wheel speed sensors used in ABS/TCS are available to the autonomous driving system also. The accelerator pedal position sensor(s) and the brake switch sensor or the brake pedal position sensor in a hybrid or fully electric vehicle are also available to the autonomous driving system and signal driver takeover request in the longitudinal direction. In addition, the ESC system introduces a steering wheel position and rate sensor, a yaw rate sensor and an accelerometer with longitudinal and lateral acceleration all of which are accessible using the vehicle controller area network (CAN) bus to the autonomous driving controller which is also a vehicle dynamics controller but with perception, situational awareness, and decision-making. It is expected that future autonomous vehicle path-tracking controllers will take over the tasks of ABS/TCS/ESC subsystems. The current technology uses a handover of control to ABS/TCS/ESC systems when they are activated.

These functions should be an integral part of the AV trajectory tracking controller with seamless operation.

Power steering systems and electric or electric-assisted power steering systems are now common in road vehicles as they are also necessary for automatic parking and lane-keeping assistance ADAS systems. While power-assisted steering requires the electric motor to operate in torque control mode, these electric motors can also switch to position control mode which is used for lane keeping and parking assistance. Using the appropriate CAN bus commands, the power steering actuator can be used to automatically steer the vehicle. For this purpose, the power steering actuation system should be designed to be able to also handle emergency lane change type maneuvers that may be required in autonomous driving. Autonomous driving will also require an automatic transmission with the ability to change the transmission state electronically through CAN bus commands. This also includes transmission gear changes for optimum performance. In most research AVs and retrofitted vehicles for autonomous operation, the vehicle's inherent automatic transmission controller takes care of the gear switching and the AV driving system can only switch state between neutral, drive, park, and reverse.

The basic Cruise Control (CC) system has been available for a long time and has advanced from a simple mechanical type control to an advanced speed controller for the vehicle. Most current vehicles are easily equipped with ACC which uses longitudinal automation and a front-looking camera/radar combination to follow a slower target vehicle in front at the desired time gap selected by the driver. These systems are now capable of operating all the way down to a complete stop (although requiring a minimum speed to be initiated first). Along with a Lane Keeping System (LKS), an ACC system provides a very basic automated driving capability in highways. As these two ADAS systems are very well calibrated by automotive OEMs, they work very well in driving situations with the decision-making still carried out by the driver. Improving this system into a traffic jam assistance which also works at very low speeds down to zero result in a very basic highway driving automation and forms the basis of some recently announced L3 driving capable series produced vehicles [1]. The natural evolution of automated driving from ADAS systems is a much safer approach as compared to retrofitting a vehicle for automated operation and re-designing the control system since automotive OEMs and suppliers have already devoted extensive development and testing effort and experience to these systems which are also highway legal. Current autonomous shuttles, for example, cannot handle speeds above 25 mph on exurban roads with 35 or 45 mph speed limits, also due to the fact that it is harder for them to map those parts of roads due to the lack of enough landmarks and due to memory limitations. ADAS systems that already exist in series produced vehicles can easily take care of automated driving in those segments of the route without the need for scan matching of a high-definition 3D lidar map.

Automatic Emergency Braking (AEB) is another ADAS and safety feature that is easily available in current series produced vehicles. It requires short-range radars also to determine dangerous oncoming target vehicles at close range. Some implementations of AEB can even steer the vehicle slightly if a collision cannot be avoided by braking alone. If the AEB system had not been disengaged in the 2018 Uber accident, for example the accident could have been avoided or could have been nonfatal [49]. Lane Change Assistance Systems (LCASs) use short range side radars to determine a collision risk during lane changing. It is clear that the presently available ADAS systems like LKS (also denoted LKAS for Lane Keeping Assistance System), ACC, AEB, LCAS, and their extensions can form the basis of an automated driving system. All the actuators, sensors, and basic lower-level control systems are already available and need to be complemented by or upgraded to a more powerful computing system with integrated, more advanced algorithms for situational awareness and decision-making. Navigation systems are also very common and easy to add to series production vehicles. An electronic horizon system can also be used instead of the navigation system. The navigation system or electronic horizon can be used to determine the route or path once the destination is selected.

1.4 Autonomous Driving Architectures

An autonomous driving vehicle architecture consists of the actuation, low-level controls, perception and communication sensors, localization sensors, localization, sensor fusion and situational awareness, computational system, and higher-level decision-making layers. One can also take a look at the hardware and software architectures separately. The software architecture will then comprise of the AV driving functions. These driving functions have to include localization to answer: “Where am I?,” user input to answer: “What is my destination,” path planning to answer: “How do I get there” and collision avoidance maneuvering to answer: “How do I avoid obstacles along my route?” Some basic architectures and rule-based approaches to decision-making are presented in Chapter 3 of this book. The rule-based approach for decision-making uses Finite State Machines (FSMs). An alternative approach is to use data-driven approaches like deep learning or reinforcement learning [50]. While the literature has an abundance of papers on data driven approaches, they unfortunately neglect the dynamic nature of the vehicle and its limitations, resulting in suboptimal path following performance accompanied by discontinuous and jumpy steering and nonsmooth motion especially when end-to-end data-driven approaches are used. The recommended alternative is to use an end-to-mid approach where the path-tracking control is taken outside the data-driven part of the implementation and, hence, made vehicle platform agnostic [51]. This book fills an important gap in this area by introducing trajectory planning and tracking methods that respect the dynamic nature and limitations of an actual road vehicle and result in physically implementable systems with smooth AV motion characteristics.

1.5 Cybersecurity Considerations

The literature review on path modeling, planning, and path-tracking control is presented in detail in the relevant chapter. We will talk briefly on cybersecurity concerns and issues. Autonomous vehicles can be hacked just like computers, and cybersecurity issues should not be underestimated. V2X connectivity that is present in AVs is an important source of cybersecurity concerns. The Security Credential Management System (SCMS) which is a security certificate is used in connected AVs to overcome cybersecurity issues due to V2X connectivity. The connected AV will trust nearby communicating agents that have the correct security certificate which like all certificates can be faked. It is, thus, possible to send wrong MAP and SpaT messages from a connected intersection resulting in the AV making wrong decisions on the location and geometry of the intersection and the signal phase. A very simple example is fooling an AV into a green phase even though the actual phase is red. It is also possible to introduce fake or ghost vehicles or sudden obstacles by sending fake locations in the Basic Safety Message (BSM) in V2V communication. This may result in the vehicle performing an emergency stop or emergency evasive maneuver even though there is no need for it. It is evident that such problems cannot simply be resolved with certificates and encryption alone. The use of a supervisory copilot that continuously monitors the connected AV and does a safety check of its planned motion is what is proposed here as a solution. This supervisory copilot (not a person but another autonomous system) continuously checks the perception sensors and compares with the communicating agent data to determine whether the communicated information is trustworthy or not. Once the immediate future part of the path including modifications for obstacle avoidance are computed, they can be checked using control barrier functions, for instance, for feasibility and also to avoid cybersecurity issues due to malicious information [52]. Control barrier certificates can also be used for the same purpose [53].

The same approach has to be used for the perception sensors whose data is fused. Support Vector Machine (SVM) computations can be used for this purpose also [54]. Note that some perception sensors can be fooled just like they are artificially generated in hardware-in-the-loop (HIL) simulations. Fake Doppler signals or lidar signals can be physically sent to misguide radar or lidar sensors. Light sources can be used to blind out camera sensors. GPS signals can be jammed or spoofed. The AV has to rely on redundant sensor data to identify the presence of an issue and in extreme cases, report the situation, pullover and stop autonomous operation.

Even though several articles have reported hacking of the vehicle CAN bus in the past, this was only possible as an interface device was physically attached to the CAN bus connector which is highly unlikely in practice [55]. The infotainment system in newer cars communicates with the outside worlds and is, thus, open to attacks. Indeed, most of the car hacking examples reported until now have been achieved through vulnerabilities in the infotainment system. If the infotainment system has the capability of access to the vehicle CAN bus, it is possible to take over control of the vehicle actuators and functions and command them remotely. This is a very dangerous situation. The main dangerous outcome of all malicious attacks on a road vehicle, especially a connected and autonomous one, is the modification of the path of the vehicle and the associated controls which may lead to fatal accidents. This means that the path-planning system and path-tracking controls should continuously check the planned path and the actual path tracking against the vehicle mission of reaching the final destination and for obstacle avoidance and for obeying rules of traffic.

1.6 Organization and Scope of the Book

This book is organized in to eight chapters. The second chapter following this introductory chapter is on the tire and vehicle dynamics, path and path-tracking modeling. The third chapter is an overview of simulation, experimentation, and parameter estimation. The fourth chapter treats mathematical modeling of the path including the generation of such models using data in the form of waypoints to be followed. Chapter 5 is on collision free-path planning and introduces methods of modifying the path to avoid obstacles. Chapter 6 introduces model regulation or the disturbance observer loop to reject road curvature as a disturbance in path-tracking control. Chapter 7 uses robust gain scheduled parameter space design and linear matrix inequality (LMI) control for path tracking. The book ends in Chapter 8 with conclusions.

1.7 Chapter Summary and Concluding Remarks

This is the first chapter of the book and forms an introduction to autonomous vehicle path planning and path-tracking control. The chapter started with an introduction to autonomous vehicles and the motivation for the book as collision free-path planning and path tracking are the most essential functions of autonomous driving. After the introduction and motivation, a brief history of autonomous driving is presented. It is seen that the two separate research directions of road vehicle automation and autonomy of mobile robots have merged together to form the basis of modern-day autonomous vehicles. Active safety systems and ADAS for series produced road vehicles are discussed briefly to show the safe and gradual approach to autonomy and intelligence taken by the automotive industry. Brief information on autonomous driving architectures and cybersecurity issues are the last topics treated in this chapter.

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