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A survey of autonomous vehicles for traffic analysis

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ABSTRACT

Autonomous vehicles stand at the forefront of technological advancement, promising to alter fundamentally how we navigate, with implications for everything from intercity logistics to daily commuting. The expected benefits of this technology include advancements in safety protocols, streamlining of traffic flow, and superior comfort for those onboard. However, the path to widespread integration is paved with significant barriers that need to be overcome. This article provides a thorough review of the historical development of autonomous driving technologies, beginning with the early vehicles powered by internal combustion engines and extending to the present excitement over Apple's Project Titan. Rumors suggest this particular project involves the creation of an electric vehicle fully capable of operating without traditional manual controls, including steering wheels and seats. The article concludes by spotlighting the potential for autonomous vehicles to enable disruptive changes in the transport sector, while also considering the myriad of challenges that must be surmounted for their adoption on a grand scale.

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1. INTRODUCTION

Recently, there has been steady progress in the artificial intelligence (AI) and especially the deep learning fields, which in turn permitted more and more sophisticated autonomous systems, especially in the fields of autonomous driving and traffic analysis. These technologies especially in the case of autonomous driving vehicles already show signs of their disruptive potential at every level of society, autonomous driving is broadly categorized into six levels of automation according to a classification system developed by SAE International. There is level 0 through 5, from no automation at all to full driving automation. The use of AI has already manifested itself in today's everyday transportation, indeed more and more car makers introduce AI-assisted driving like Tesla's Autopilot which has been a standard feature of every manufactured Tesla vehicle since 2014 and is a level 2 autonomous driving system that has partial automation features like cruise control, automatic lane change, and self-parking. Other manufacturers (like BMW, Mercedes, and Peugeot) only have some level 2 features at the moment, although Mercedes-Benz claims that its drive pilot system for conditional automated driving is at level 3 and already available for the S-class and the EQS. The need for mobility in ever-increasing crowded cities has led to more traffic jams, accidents, and overall more pollution and harm to the environment, a solution for safe and efficient traffic lies in the development of mature and reliable intelligent transport systems. Of course for the deployment of these systems, autonomous driving is a necessity but is not sufficient, it has to be accompanied by traffic monitoring and analysis systems for both urban environments and highway roads between urban centers. Before the advent of the automobile, individuals relied on predominantly muscle-powered modes of transportation. Among these methods were primitive contrivances such as the travois, the sled, or the sledge. The first wheeled vehicles are dated from antiquity, more than 4,000 years ago, in the form of two and four-wheeled wagons. These vehicles eventually became steerable in a Celtic invention that was adopted and spread throughout the Roman empire, the Roman rheda, due to its excellent infrastructure, especially roads. In the 15^{th} century road traffic began its resurgence in Europe to levels not seen since the Roman Empire, thus the need for a lightweight and fast carriage, the coach, originating from the Hungarian town of "Kocs" spread throughout Europe and was in use until the dawn of the 20^{th} century.

2. 1880-1930: THE BIRTH OF THE AUTOMOBILE AND THE EMERGENCE OF BASIC AUTOMATION

The dawn of the automobile was heralded by pioneering inventors and engineers such as Karl Benz and Gottlieb Daimler, who developed some of the first practical automobiles [1]. These early vehicles were manually operated, but the era also saw the introduction of rudimentary automated features aimed at improving performance, safety, and convenience. For instance, the float-feed carburetor, patented by Wilhelm Maybach in 1893, allowed for more efficient fuel delivery to the engine. Similarly, the development of the high-voltage magneto ignition system by Robert Bosch in 1902 provided a more reliable and automated means of igniting the fuel-air mixture in engines. One of the most significant advancements in vehicle automation during this period was the invention of the electric self-starter by Charles Kettering in 1911, which eliminated the physically demanding and often dangerous process of hand-cranking to start the engine. These early forms of automation were critical in enhancing the functionality and usability of automobiles, which contributed to their widespread adoption. While the real beginning of autonomous vehicle development was not realized until much later, the foundations for driverless technology were conceptualized during this time. The concept of automated control systems for vehicles can be traced back to radio-controlled torpedoes and boats developed in the late 19^{th} century [2]. These early experiments with remote control and guidance systems represented the primitive beginnings of what would eventually evolve into sophisticated autonomous vehicle technology. While the primary focus of the era was on the mechanization of vehicle production and increasing accessibility, it also sowed the seeds for the concept of autonomous vehicles. The first semblance of driverless technology can be traced back to experiments in the early 20^{th} century, such as the radio-controlled 'American Wonder' demonstrated in 1925 by Francis Houdina, which hinted at the potential for vehicles to be controlled without direct human intervention [3]. One notable invention that paved the way for future automation was the rudimentary cruise control device, patented in 1900 by Ralph Teetor, which allowed for the control of a vehicle's speed without the driver's constant input.

3. 1930-1970: THE PREDECESSORS OF AUTONOMOUS TECHNOLOGIES AND EARLY EXPERIMENTS AND PROTOTYPES

The first mention of autonomous driving and self-driving vehicles appeared at the World Fair that took place in New York in 1939 where general motors unveiled "The World of Tomorrow" which consisted of 35,000 square feet of a vast miniature model of what America would appear in the future, designed by Norman Bel Geddes who envisioned vast cities in a streamlined style connected by steady flow multi-lane highways and dotted with semi-automated vehicles [4]. Geddes expands on this in his book *Magic Motorways* [5], where he sees a future that needs to "eliminate the human factor in driving", for the technical advancements of automobiles only make them more dangerous to humans because their nature and physiology do not change, hence the need to involve humans the least amount possible in the process of driving. Indeed according to Geddes future cars will prevent drivers from turning into traffic when they shouldn't and assist them in passing through intersections without slowing down or endangering themselves or others, we can already see here the first formulation of what would shape up to be systems like an automatic lane change, cruise control or lane centering.

The 1950s witnessed further advancements with the experimentation of autonomous vehicles by radio control, such as the project led by RCA Labs in collaboration with the State of Nebraska, which demonstrated a car that could follow a wire embedded in the road in 1958. By the 1960s, the United Kingdom's Road Research Laboratory began testing driverless cars on a track equipped with magnetic cables. These early prototypes and experiments not only demonstrated the technical feasibility of certain aspects of vehicle automation but also spurred public interest and discourse around the concept of self-driving cars, setting the stage for the subsequent development of autonomous vehicle technologies.

Established in 1946, SRI International, previously recognized as Stanford Research Institute, is a Californian research center. It conducts research and development across a multitude of disciplines such as AI, computer science, and computer vision. Servicing both government and private entities. Among its notable innovations is Shakey the robot [6], [7], the pioneer autonomous mobile robot equipped with integrated vision, developed from 1966 to 1972. The first model was completed in 1969 and is equipped with a TV camera, an optical rangefinder, and cat-whisker-activated bump sensors. It was operated by radio via an SDS-940 computer and used two world models for interaction and problem-solving purposes. These included a map-like grid model and an axiom model for language communication systems. A second iteration was launched in 1971, featuring identical hardware but with a more advanced PDP-10 computer. This model utilized a single axiom model in contrast to its predecessor. The robot's system was structured hierarchically with five main levels. The first level encompassed the physical structures such as the robot and the communication system. The next level was made up of low-level actions (LLA), which are basic function-controlling programs like "ROLL" or "TILT". The third level contained a set of intermediate-level actions (ILA), pre-configured LLA packages that represented complex capabilities like "PUSH" or "GO TO". The fourth level was focused on problem-solving and planning, where the symbolic planning system (STRIPS) planning mechanism created a sequence of ILA's for specific tasks or problem-solving. Finally, the fifth level involved a program known as planning exercise (PLANEX) that oversaw and implemented the ILA's.

4. 1970-1990: PROGRESS IN ROBOTICS AND COMPUTER VISION

The Stanford Artificial Intelligence Laboratory is a world-renowned research lab that is at the forefront of AI research. It has an extensive history of innovation with significant contributions to the field, like for example, it has contributed to the development of, the Lisp programming language which is still widely used in AI research today or Shakey the robot, ARPANET, the AlphaGo program, which defeated a human Go champion in 2016. SAIL is home to some of the world's leading AI researchers and offers several educational programs. It was founded in 1963 by John McCarthy, one of the founding fathers of AI. It is located at Stanford University in Palo Alto, California. The Stanford cart [8] is an electric vehicle developed at Stanford from 1960 to 1963 and at SAIL from 1964 to 1980, it is remotely controlled via a citizen-band radio link to a PDP-KL10 processor and with a black and white TV camera as the vision system. The Stanford cart goal is to drive through a 20-meter course and arrive at a destination while avoiding small and large obstacles, and it takes approximately 5 hours for a complete run at about 1 meter per 15 minutes. Five software components are necessary to achieve its goal, a camera calibration program, an interest operator that picks out 30 features from each image taken, a correlator for finding matching features in other images, a camera solver that uses stereo information to determine any object distance from the camera and its displacement, a navigator that plans a path to the destination while avoiding obstacles. Located in California, Caltech's Jet Propulsion Laboratory is a research center funded by NASA. It is and has been responsible for many of the most important space missions in history, including the voyager probes, the mars pathfinder, and the curiosity rover. JPL was founded in 1936 by Caltech professor Theodore von Kármán and a group of rocket enthusiasts. The laboratory's early work focused on developing rocket engines and guidance systems for military applications. However, after the launch of Sputnik in 1957, JPL began to focus on space exploration. The first practical application of autonomous driving and navigation comes from the JPL intended to develop a semi-autonomous vehicle for remote planetary exploration, the JPL made a "breadboard" robot for testing and demonstration purposes [9]. The robot vision system hardware consists of a pair of solid-state charge injection devices (CID) cameras for stereo vision, a laser range scanner to estimate distances, RAPID a dynamic random access memory, and an SPC-16/85 computer. The vision software consists of multiple subsystems, a semantic network [10], scene segmentation [11], [12], stereo correlation [13], [14], and camera calibration. Similarly, the Stanford cart also uses stereo vision to navigate its environment, contrary to the Carnegie-Mellon University (CMU) Rover which uses a set of different sensors (camera, sonar, infrared sensor) and is more capable.

The Rover [15] is an effort by CMU's Robotics Institute to build on the Stanford cart, with 3 individually steerable wheels for improved mobility which confers the Rover 3 degrees of freedom, the CMU Rover improves on the situational awareness of the Stanford cart by adding several infrared proximity sensors and a long-range sonar on top on the TV camera with pan, tilt and slide controls. More powerful processing power is also provided with a VAX 11/780 computer and an ST-100 array processor to make it at least 10 times faster than the Stanford cart which needs 15 min of processing to move 1 min. Hardware-wise, each wheel is equipped with 2 motors and 2 Motorola 6,805 processors, one per motor, next is the conductor which is a Motorola 68,000 processor responsible for operating each motor processor, the simulator is another 68,000 that estimates the robot's position, and the controller another 68,000 produces the desired position. Each sensor is controlled by a 6,805 and communications are supervised by a 68,000 by an infrared link that connects to the VAX 11/780 which does all the heavy processing.

The mid-'80s also saw the development of CMU Navlab [16], a complete laboratory for navigation and computer vision and a bigger and better version of the six-wheeled Terregator [17]. The first iteration of NavLab, NavLab I, is a Chevrolet van controlled by computers with humans in the loop where humans can take over at any moment and can reach top speeds of up to 20 m.p.h. In terms of loadout, it is equipped with onboard computers: three sun computers, a warp processor, a safety driver, and four researchers in the back with a computer each, onboard power: two 5,500 W generators, a color camera, a laser range finder and finally an evolving controller: it permits the computers to steer the van by controlling the hydraulic and electric servos, can set the speed and ask for the current position estimate, it will eventually integrate global positioning system (GPS), inertial guidance and even computer temperature and hydraulic pressure. The NavLab software consists of three main components, a color vision module for finding and following roads [18], a 3-D perception module for obstacle avoidance [19], and the CODGER whiteboard module [20]. The color vision module is based on two algorithms, one for road edge extraction [21], [22] and the other for color classification [23], classifying pixels as road or not based on color with more than one model for each class due to the variety of conditions (rain, day/night cycle, and the shadow of other objects), then the road is located with the aid of an area voting technique using a 2-D parameter space with similarities to a Hough Transform. The color vision algorithm designed to recognize and detect roads and intersections is a supervised classification applied to road following, it was tested on Navlab and has a top-mounted color camera and is tilted towards the ground for the explicit purpose of path following and staying on detected roads. The algorithm has four general steps, preprocessing where the original full-resolution camera image is reduced for faster processing, color model formulation with road and off-road regions and pixels in these regions are then assembled into sets of similar colors, a Gaussian model is used to fit each set and each of these models are then fed as input to the next step. Classification takes these previous Gaussian color models and the reduced color image as inputs and computes the probability for each pixel to be in the road class or not, this process is called Bayesian classification. In road model matching, status, certainty, autonomy, relatedness, and fairness (SCARF) generates several road candidates and matches them with the road-surface probability or likelihood image obtained during classification, then the best matching candidate is used as input in the path-planning algorithm.

Vertical interval test signal (television) (VITS) [24] is the computer vision platform for the autonomous land vehicle, it is an eight-wheel drive diesel-powered mobile robot, as a sensor suite it has a charge-coupled device (CCD) color camera and a laser range scanner. In 1985 and 1986, ALV demonstrated its capability for road-following on the Martin Marietta test track and covered its entire length, 4.2 km at speeds up to 10 km/hour. On the course, Alvin can, switch between a road-based and range-based following, avoid obstacles and speed up to 20 km/hour, vary its speed, stop or turn around completely, negotiate hairpin curves, and travel over two different types of road. Alvin is quite a massive robot, 4.2 meters long and 2.7 meters in width with a height of 3.1 meters in height, it weighs more than 7 tons. On the inside, Alvin hosts multiple types of computers and processors, VITS uses a vicom image processor allowing for complex operations like convolutions, and image algebra (addition or subtraction of images) to be done at frame rate speed. The vision system works by building a model of the road from video and range data, this model is then transferred to a reasoning module that uses extra information like the current position or even speed. And finally, it generates a trajectory for ALV to follow.

5. 1990-2010: RISE OF AUTONOMOUS VEHICLE COMPETITIONS

In the '90s, CMU developed Navlab 2 [25] based on a Humvee chassis with three Sparc 10 and two 68,000 computers, with similar sensors to the Navlab 1 it can reach 6 m.p.h over rough terrain and 70 m.p.h on a road. The introduction of the portable advanced navigation support compact system powered by the car's cigarette lighter, allowed Carnegie-Mellon's researchers to log over 6,000 miles of autonomous driving in less than 6 months. The portable advanced navigation support platform is composed of the following items, the Sparc LX class portable workstation, an HC11 processor for low-level motor steering and safety monitoring, a Sony DXC-151A color camera, and for local/global positioning a Trimble SVeeSix differential GPS paired with an Andrew Corporation Autogyrož fiber optic gyroscope. The Portable Advanced Navigation Support platform can run several computer vision algorithms for collision warning, steering, autonomous control, Alvinn [26] is a backpropagation neural network composed of 3 layers for the task of following the road and keeping in lane, it learns the relationship between low-resolution images of the road and vehicle steering command, it can learn to drive by observing the steering patterns of a real driver for five minutes augmented by artificially generated road images for reliable performance. An issue with Alvinn networks is that they can only perform well if road conditions and sensor input remain similar, to overcome this problem Maniac [27] a modular neural superstructure that includes multiple Alvinn networks is introduced, the goal is to combine data from different Alvinn networks to achieve seamless and transparent navigation between road types and simultaneous use of different sensors. Aurora [28], [29] is a downward-looking computer vision system designed to warn of lane departure incidents, it is capable of providing accurate lane position despite bad meteorological conditions, and even when lane markings are degraded or worn, using a color camera Aurora computes the Time to Lane Crossing which is how long it takes for a vehicle to cross a lane and is measured per image dependent on the vehicle's lateral position and its velocity such as if it falls below a certain speed, an alarm is triggered to warn the driver through visual and audible cues.

5.1. The 1995 trans-continental journey ”no hands across America”

Navlab 5 [30] was an autonomous vehicle for the 1995 trans-continental journey ”No Hands Across America”, achieving 98.2% of the total distance of 2,849 miles i.d 2,797 miles from Pittsburgh to San Diego. The vehicle is a 1990 Pontiac outfitted with the portable advanced navigation support platform described above, and the rapidly adapting lateral position handler steering system that adopts the following strategy. First is image sampling, where a scene is captured by a color camera that is mounted near the rear-view mirror and is cropped of irrelevant parts to only process a trapezoid image of the road ahead into a 30×32 pixels image of the important features (usually lane markings). Second is road curvature determination, where RALPH hypothesizes a curvature, and subtracts it from the 30×32 image to see if the result appears to have ”straightened” features in which case the hypothesis is correct. Third is determining the vehicle's sideways displacement in relation to the center of the lane by using template matching, it compares the resulting image of the difference obtained during the road curve determination step to the template generated during the centering step.

5.2. The 1997 automated highway free agent demonstration presented by the US national automated highway system consortium

Navlab 6, 7, 8, 9, and 10 [31] are all part of the 1997 automated highway free agent demonstration presented by the US national automated highway system consortium, where took place different complex maneuvers like lane changing, entry and following, speed controls, and obstacle detection. Navlab 6 and 7 are fully automated Pontiac Bonnevilles, Navlab 8 is a semi-automated Oldsmobile Silhouette and Navlab 9 and 10 are fully automated New Flyer city buses, and to a great extent all systems and components are nearly identical, they include the RALPH vision system for road following, a mechanically scanned front radio detecting and ranging (RADAR) and its software for detecting and scanning long range targets, four side short range RADARs, a rear looking ladar (laser detection and ranging) and after sensing the environment remains the difficult task of making a decision like when to change lanes, when to speed up and so on, to that end Rahul Sukthankar developed the rule based driving system Sapient [32], where each object in the environment is seen as a ”reasoning object” that tracks variables like speed or distance between other objects and at each time step any ”reasoning object” casts weighted votes for or against any actions to be taken, thus making any action graded, a strongly rated turn would be sharper than a moderately rated one.

5.3. The program for European traffic with highest efficiency and unprecedented safety

From 1987 to 1995, the European Eureka Program for European traffic with highest efficiency and unprecedented safety project PROMETHEUS with funding of more than 700 million Euros and the participation of several car manufacturers and universities from different European countries, aimed at defining the state of the art of autonomous vehicles. Participating in this project was E.D. Dickmanns *et al.* a pioneer in the 80s of autonomous vehicles with the VaMoRs van weighing more than 5-ton [33] and developed at the University of Bundeswehr München UniBwM and the 7.5 tons Mercedes D811 van VITA [34], both of which led to in 1994 to the VaMoRs-P of UniBwM [35], a Mercedes S-class SEL500 of Daimler-Benz, and its twin vehicle VITA II [36], the latter being the official common European demonstrator vehicle for the last demonstration of PROMETHEUS in Paris in 1994. In this final demonstration, VaMoRs-P and its twin VITA II drove for at least 1,000 km, on a highway in rather busy traffic, and with the presence of a safety driver, the system demonstrated lane changing and autonomous overtaking. The VaMoRs-P/VITA II computer vision system utilizes a 4-D method for dynamic vision and allows for an intelligent combination of forward and backward regions and up to 5 obstacles and vehicles are detected and tracked at a maximum of 100 m range. Hardware-wise the computer vision system consists of about 60 transputers, 24 16-bit T-222, and the rest 32-bit T-805, four CCD cameras, two in the front and two in the rear, providing multifocal vision and rapid back and forth viewing direction controls such that the two sets of cameras can focus on areas of special interests thus drastically reducing data loads. Software-wise, the system consists of the KRONOS package for feature/edge extraction, the object detection and tracking module [37], the road detection and tracking module that uses a time-varying sliding model to recognize and predict upcoming lane curves and estimate their curvature correctly [38], [39], the dynamic database module for data exchange between system components, the vehicle control module responsible for generating control outputs for autonomous driving and finally the behavior decision module and Situation Assessment module. Also part of the PROMETHEUS project is the work of Shwartzinger *et al.* [40] where they developed the CARTRACK system that can perform detection, tracking, and identify the back of a vehicle by exploiting the symmetry of the rear of most cars. The CARTRACK system is composed of two parts, the first module searches for regions of interest with a high degree of symmetry and uses two methods, one based on intensity values and the other based on a feedforward neural network SEED c, and the second module extracts features from a region of interest and matches them with a generic feature-based model of the object, in this case, the rear of a car. In 1995, VaMoRs-P drove autonomously from Munich to Odense (Denmark) for a total distance of 1,600 km [41] in which it was used 95% of the time, in this setup "autonomous driving" is defined as performing the following tasks, collision avoidance, automatic lane keeping,self-supervision, longitudinal control and finally put a stop to the automatic controls and give them back over to the driver.

GOLD [42] or the generic obstacle and lane detection system is based on stereo vision for both lane and obstacle detection, integrated into the ARGO and the MOB-LAB [43], it is an offshoot of the Italian research teams that participated in PROMETHEUS, it is equipped with two front cameras out of four total, along with computers, monitors and a control panel. GOLD's computer vision system is composed of three parts, the first consists of removing the perspective effect from both left and right stereo images in what we call stereo inverse perspective mapping (IPM). Second is lane detection using road markings brightness and feature extraction by exploiting lane and road geometry. Lastly, obstacle detection is implemented, which relies on the identification of a pair of triangles derived from the stereo IPM phase. In this phase, the disparity between the left and right stereo images converts perfect square obstacles into triangles. Afterward, polar and radial histograms are utilized to pinpoint the contact points between the obstacle and the road. This process then determines the distance of the obstacle through a straightforward threshold. On the hardware side, GOLD is composed of a low-level processing system paprica, and a medium-level processing SPARC-based host computer. The affordable, special-purpose parallel processor used for analyzing and checking images is constructed with a massive parallel infrastructure that includes 256 processors. Its design uniquely suits it for applications where quick response times are vital. Further, its reduced power intake makes it perfectly suitable for use in mobile computing applications. The GOLD system was tested on the MOB-LAB for more than 3,000 km, on freeways and non-urban roads at speeds up to 80 km/h.

5.4. The DARPA grand challenge (2004, 2005)

Constructed on the medium tactical vehicle replacement MK23 truck framework from Oshkosh, TerraMax [44] is a self-navigating vehicle. It valiantly completed a 132-mile desert course in the 2005 DARPA grand challenge [45], an earlier model also competed in the 2004 version of the same challenge. The birth of TerraMax was a group effort, with rockwell collins providing the intelligent vehicle management system (iVMS), the University of Parma's VisLab contributing the visual system, and Oshkosh Corp delivering the vehicle and the required infrastructure. The iVMS is the nucleus of TerraMax, facilitating a range of autonomous operations by interfacing with diverse hardware and software elements. It governs the vehicle's steering, brakes, and throttle, devises the route in real-time using a type of rapidly exploring random trees (RTT) path planner [46] and sensors, detects barriers using vision, light detection and ranging (LiDAR) and steers the vehicle's mode and navigation. Its computer vision relies on a trinocular system, where feeds from three cameras are sent to a computer that selects the optimal pair for stereo vision. This system uses image disparity to estimate the typical incline of the terrain and identify obstacles, which is further refined by LiDAR technology.

Thrun *et al.* [47], Stanley an alternate autonomous vehicle, emerged as the champion of the 2005

DARPA grand challenge, developed at Stanford it is based on a 2004 Volkswagen Touareg R5 TDI. Stanley boasts a computing hub of 6 Intel Pentium M processors, and actuators for throttle, brakes, steering, and gear shifting. A custom roof rack houses its sensor suite, which includes five laser range finders, a color camera, two RADAR sensors, an L1/L2/Omnistar HP receiver GPS positioning unit, and a six-degree-of-freedom inertial measurement unit (IMU). In emergencies, DARPA's E-stop system, equipped with three GPS antennas and a radio antenna, allows any chase vehicle to stop Stanley. Stanley's software operates on a decentralized structure with 30 independent modules. This system can be segmented into six layers: sensor interface, control, perception, vehicle interface, user interface, and global services. The sensor interface layer adds timestamps to all sensor data and contains the RDDF file with course coordinates. The perception layer converts sensor data into two-dimensional maps for determining safe speeds and finding roads. It uses an unscented Kalman filter (UKF) vehicle state estimator to estimate the speed, location, and orientation of the vehicle. The control layer, with the path planner module as a critical component, oversees the brake, steering, and throttle. The vehicle interface layer establishes connectivity with every element and system within the vehicle, while the user interface layer incorporates features like the touchscreen module and remote E-stop. Conclusively, it's the global services layer that imparts numerous services such as communication, time balancing, health management, power regulation, and data recording to all modules.

5.5. The DARPA urban challenge (2007)

The BOSS vehicle [48] won the 2007 DARPA urban challenge and was developed by the tartan racing team of CMU. In this challenge, competitors were tasked with developing a fully autonomous vehicle capable of navigating 60 miles of urban traffic and environments. It was based on a 2007 Chevrolet Tahoe modified to accommodate 17 sensors mounted on the chassis to provide 360-degree coverage, a combination of LiDAR, RADAR, and GPS. For processing, BOSS relies on a CompactPCI computer with ten Core2Duo processors, this processing power allowed for the software i.e., mission planning, perception, motion planning, and behavioral executive systems to run in real-time robustly and reliably. Moreover, BOSS depends on crucial software elements for independent driving in urban settings. These include the 'world model', a depiction of the BOSS vehicle itself, vehicles being tracked, and the road's location with static and dynamic barriers. Next, is the "moving obstacle detection and tracking" algorithm [49], which is composed of two layers, the sensor layer, and the fusion layer, with the purpose of this algorithm that fuse sensor data to generate several possible objects to add to the dynamic obstacle list. Following that, the 'motion planning' element aids in maneuvering the vehicle in the environment by pinpointing a target and producing a series of trajectories that are free from collisions. The most suitable path is then chosen, considering factors like its nearness to barriers, the distance from the central path, and the level of smoothness, among others. Next in line is the 'intersection handling' module–an integral part of the behavioral executive system, primarily responsible for controlling priority at crossroads. It uses the world model and the vehicle's known route to decide the sequence of intersection preference. Finally, the 'error recovery' module ensures the BOSS vehicle's seamless driving, effectively adapting to its surroundings despite unexpected conditions or unauthorized actions.

The team LUX [50] vehicle is a Volkswagen Passat B6 equipped with three Ibeo laser scanners, two in the front and one in the rear for 360 degrees coverage, a GPS for geo-location, and two electronic control units (ECUs) for processing. The laser scanners can simultaneously scan four planes, and each scan may have up to 15,520 scan points, also they can accurately classify the following objects up to 200 meters, objects, lane markings, ground, dirt, rain, and snow. Path planning is done by converting a mission route into a driveable path using a navigation map created from the route network definition file and mission data file, in addition to a surroundings map created from the sensors data.

5.6. The MilleMiglia in automatico tour

The ARGO is an experimental autonomous lancia thema passenger car [51], its primary objective is active safety but also autonomous driving, ARGO consists only of passive sensors, two cameras, a speedometer, a commercial PC with a Pentium II processor to keep costs down, a stereo loudspeaker and a led-based control panel that acts as an active warning system to the drive and an autonomous steering device that consists of an electric motor connected to the steering column by a belt. The ARGO computer vision system performs two main tasks, lane and vehicle detection, using monocular images. Lane detection is done through feature extraction and model matching, first, preprocessing the road image to remove the perspective through Inverse Perspective Mapping is needed to obtain a top-down view image of the road, the next step is low-level processing comprised of feature extraction using brightness to obtain a binary map of road markings and road geometry extraction where chains of 8-connected non-zero pixels are approximated by a polyline. Next, we engage in high-level processing, which includes feature filtering and selection, the connection of polylines, choosing the most suitable representative, rebuilding missing data, and model fitting. Each polyline undergoes a filtering process based on continuity constraints with polylines from earlier frames, and similar ones are then linked. Every combined polyline gets a score based on length and angular coefficients. The polyline with the top score is chosen as the ideal fit for the line marking. In instances where the selected polyline doesn't entirely accommodate the marking, we use a parabolic model to extend it, enabling it to span the entire image. Vehicle detection is done using symmetry and bounding box detection where an area of interest is searched for edge and vertical symmetries, then the bottom corners of the bounding box are identified before finding the top corners and finally localizing the vehicle. Tracking is the last part of the vision system and is performed using maximizing the correlation between the bounding boxes of previous frames. To test the performance of the ARGO, a journey of 2,000 km across the Italian highway network, the "MilleMiglia in automatico tour", was carried out in June 1998 where ARGO drove itself more than 90% of the time in varying scenarios, including different weather conditions, terrain (flat or hilly terrain) and traffic (sparse or dense).

6. 2010-2020: THE AUTONOMOUS REVOLUTION BEGINS

BRAiVE [52], [53] as in brain drive is an autonomous vehicle developed by VisLab in 2010, its objective is to function as a creation platform for advanced driver support processes such as locating parking spots, implementing reverse operations, detecting potential collisions, and so forth. The BRAiVE sensor suite is composed of 10 cameras, 5 laser scanners, 1 RADAR, 1 GPS+IMU, and 1 e-Stop system, its sensor suite has a high-level integration making it look like an everyday vehicle with a 360 degrees coverage. Processing consists of 3 Mini ITX computers and connected to the sensors and/or the CAN bus by 2 ethernet ports and 2 firewire ports. Actuation is done via two main ways, first, the X-by-wire (XBW) system is comprised of actuators for automatic cruise control, an electronic stability program, and electric power steering, these can be controlled using CAN messages, BRAiVE can behave as an autonomous or normal car depending on whether the XBW system is on or off. Second, a dSPace micro autobox that acts as a middle-man between PCs and actuators via CAN messages, is responsible for the e-Stop system and other actuators, especially those responsible for headlights, stop lights, indicators, and wipers.

6.1. The VisLab intercontinental autonomous challenge

In cooperation with piaggio, piaggio porter electric power vehicles were used for the VisLab intercontinental autonomous challenge, a 13,000 km drive from Parma to Shanghai [54], [55]. For this journey, the party traveling is composed of four autonomous vehicles (two on the road and two as backups), seven support vehicles (four RVs, two trucks to carry tools and a mechanical shop, and a truck able to carry two autonomous vehicles). The two autonomous vehicles although similar have different goals, by following a leader-follower approach, the leader collects the first batch of data from its sensors however it is not fully autonomous and relies on human intervention to define the route and in special situations, the second vehicle follows the route defined by the leader and uses its sensors to rectify its position, however when the leader is not visible to the follower, the latter uses GPS waypoints generated by the leader to define the route. The sensing suite of the Piaggio autonomous vehicle consists of seven cameras and four laser scanners for lane marking, traffic, and obstacle detection. The vehicle also relies on a GPS and an IMU for localization, a radio for communication between vehicles, and a solar panel on the roof to power the different systems.

6.2. The European V-charge project

The V-charge project [56] paper outlines the creation of an automated vehicle designed for valet parking and recharging. It covers the platform setup and the mapping, perception, and planning systems. A volkswagen golf, equipped with budget-friendly, close-to-market sensors, serves as the vehicle. The sensor suite comprises 12 sonars for short-range detection, a front-facing stereo camera, and 4 fish-eye cameras for a 360-degree view. These sensors contribute to generating a 3D model of the vehicle's surroundings, which forms the foundation for the mapping, perception, and planning systems. The system has been tested across various settings, such as city streets, parking garages, and charging stations, demonstrating its ability to navigate safely and perform valet parking and recharging. The mapping system generates a layered environmental map for both localization and planning. These layers include a sparse map, a collection of sparse 3D points created using the speeded up robust features (SURF) algorithm, and a dense map that balances representation accuracy with computational efficiency. The dense map is constructed in two steps using depth maps from fisheye cameras [57] and an algorithm that uses voxels and global convex optimization [58]. The RoadGraph [59], a directed graph, represents the road network for local and global path planning. The perception system localizes the vehicle by minimizing the error between two sets of SURF keypoints and descriptors – one from observed images and the other from points on the sparse map close to a predicted pose. This process uses the gP3P/gPnP method [60]. The system also utilizes situational awareness, relying on dense stereo from a Bosch camera, temporal stereo matching, object detection and mapping, and map fusion and dynamic objects to react to its rapidly changing surroundings. The planning system uses the RoadGraph to carry out tasks assigned by the mission planner, such as on-lane driving or parking maneuvers. The trajectories are then passed to a motion control module, which adjusts steering angle and acceleration as needed.

6.3. Recent industry projects

Founded in 2009, Waymo stands as a subsidiary of Alphabet Inc. and occupies a prominent position at the forefront of autonomous vehicle innovation. Distinguishing itself as a leader in driverless car advancement, Waymo has effectively amassed an impressive cumulative mileage of over 20 million miles on public roadways. Notably, it is poised on the cusp of attaining Level 5 autonomy, the zenith of automation, wherein human intervention becomes redundant. This starkly contrasts with prevailing technologies such as cruise control and lane-keeping systems, which invariably necessitate continuous human vigilance. Waymo's technological framework rests upon an intricate amalgamation of sensor arrays, notably encompassing LiDAR, cameras, and RADAR. LiDAR, operates through laser pulses to estimate an object's distance and velocity. Simultaneously, the ensemble of cameras endows a high-fidelity portrayal of the surroundings, while RADAR offers robust motion-tracking capabilities resilient to diverse lighting and climatic conditions. Complementary to this sensor suite, Waymo's system interfaces with GPS data and features a mechanism attuned to identifying auditory signals emanating from emergency service vehicles. In its current developmental phase, Waymo's technology is undergoing rigorous testing across multiple urban areas, including Mountain View, San Francisco, and Palo Alto. Of note is the strategic alliance with Jaguar Land Rover, culminating in the retrofitting of 20,000 electric Jaguar I-Pace vehicles, earmarked for deployment as autonomous robo-taxis. The evolution of autonomous vehicles constitutes a dynamic domain, where Waymo stands as a pivotal vanguard. As their pioneering endeavors manifest substantial progress, the realization of a driverless automotive landscape appears increasingly plausible on the immediate horizon.

Baidu, a well-known tech giant in China, has embarked on a bold endeavor in the field of autonomous vehicles, termed ”Apollo.” This unique venture is open-source, with its code accessible to all on GitHub. The Apollo project includes a range of vital systems, such as perception, high-definition (HD) mapping, localization, planning, and control, among others. It has been formulated with collaboration in mind, with a host of prominent companies such as Velodyne, Bosch, Intel, Daimler, Ford, Nvidia, or Microsoft joining Baidu in this undertaking. Apollo's main objective is to create a unified platform where manufacturers, startups, and research institutions can pool their data and resources to induce innovation and growth in autonomous technology. Parallel to Baidu, Udacity, an educational platform, has set in motion a comparable open-source project for self-driving cars. This project, similarly accessible on GitHub, is dedicated to aiding the collective initiatives in developing the future of autonomous vehicle technology, prioritizing accessibility and partnership.

Introduced in 2014, the Audi A7 piloted driving system has accumulated an impressive tally of over 1 million miles, underscoring its extensive real-world application. The system's architecture seamlessly integrates a sophisticated array of cutting-edge technologies. Comprising LiDAR, RADAR, cameras, ultrasonic sensors, and HD maps, the comprehensive sensor suite facilitates a nuanced and complete perception of the environment. This encompasses intricate tasks including meticulous mapping, precise object detection, and holistic spatial awareness. Within this framework, deep learning methodologies, notably convolutional neural networks and recurrent neural networks, amplify the interpretation of sensor data. They empower the system to excel in complex undertakings like object recognition, lane detection, and predictive analysis. The system's decision-making process artfully merges rule-based algorithms with machine learning paradigms, harnessing real-time sensor inputs, environmental cues, and dynamic traffic variables to meticulously chart optimal trajectory paths. Rigorous validation, involving both simulated scenarios and real-world trials, serves as a testament to the system's robustness, safety, and adaptability in diverse driving scenarios.

Unveiled by Mercedes-Benz in 2015, the F 015 luxury in motion embodies a pioneering concept in the realm of electric cars. Its innovative design centers around a self-driving luxury experience, carefully curated to envelop passengers in a lavish lounge-like ambiance. This autonomous prowess is facilitated by a sophisticated amalgamation of sensors and AI software, empowering the vehicle to independently navigate roads and adeptly circumvent obstacles without human intervention. The F 015 exudes an avant-garde and futuristic aesthetic and its sleek form is enhanced by a panoramic glass roof, offering occupants an unobstructed view of the sky. Within, the interior boasts a spacious and opulent layout, featuring seating in a 2+2 configuration that can pivot to foster face-to-face interactions. Additionally, a substantial touchscreen display empowers occupants to seamlessly manage the vehicle's functions. The F 015 draws its propulsion from a 200 kW electric motor, delivering an impressive range of 310 miles. Safety is a paramount consideration, evident through an array of protective features including automatic emergency braking and lane departure warnings, reiterating the vehicle's dedication to ensuring safety standards.

Uber's venture into the realm of autonomous vehicles has been characterized by a sequence of deliberate actions and progressions. Back in 2015, the company embarked on its self-driving aspirations with the establishment of the Uber advanced technologies group (ATG), headquartered in Pittsburgh, Pennsylvania. This marked the genesis of Uber's dedicated research and developmental undertakings within the autonomous driving domain. In 2016, a notable stride occurred as Uber introduced its autonomous vehicle testing to the public arena by deploying a fleet of self-driving Volvo XC90 sports utility vehicles (SUVs) onto the streets of Pittsburgh. This move bore considerable significance as it afforded passengers the pioneering opportunity to experience rides in self-driving cars, albeit with a human safety driver accompanying them in the vehicle. However, in March 2018, Uber faced a substantial setback when one of its self-driving test vehicles was involved in a tragic accident in Tempe, Arizona. This unfortunate incident prompted Uber to temporarily halt its autonomous testing program across various locations. Nonetheless, in the subsequent years, Uber remained committed to advancing its autonomous vehicle technology, with a particular emphasis on enhancing safety protocols and technological capabilities. By December 2020, the company resumed on-road autonomous testing, albeit in a controlled capacity, bolstered by heightened safety precautions. In a pivotal strategic move, in April 2021, Uber disclosed its decision to divest its self-driving unit, Uber ATG, to Aurora, a prominent entity specializing in self-driving technology. This shift signified a significant transformation in Uber's approach, emphasizing collaborative partnerships in the realm of autonomous mobility, rather than exclusively developing its proprietary autonomous technology.

Lyft, a renowned provider of ridesharing and on-demand transportation services, has also embarked on an ambitious journey in the realm of autonomous vehicles, mirroring the endeavors of its peer, Uber. Lyft is actively engaged in research and development efforts focused on self-driving cars, with a strategic goal of achieving level 5 autonomy. This level of autonomy implies a vehicle's ability to operate entirely autonomously without any human intervention. One of Lyft's key collaborators in this autonomous mobility pursuit is Aptiv, the latter primary objectives encompass the creation of vehicles with level 4 and/or level 5 autonomy. In addition to its endeavors in autonomous driving, Aptiv offers an array of products, including short-range inter-vehicle communication modules, a vital aspect of connected and autonomous vehicle ecosystems. Notably, Aptiv has strengthened its position in the self-driving car domain through strategic acquisitions. It recently added two significant companies, Movimento and nuTonomy, to its portfolio. These acquisitions underscore Aptiv's commitment to advancing autonomous technology and its role in shaping the future of mobility.

The Tesla Autopilot, initially introduced in 2015, serves as an advanced driver assistance system. Its primary objectives encompass aiding drivers in maintaining lane position, ensuring a safe separation from other vehicles, and providing automated deceleration and acceleration functions. Nevertheless, its categorization as an automotive engineers (SAE) level 2 driver assistance system underscores that the ultimate responsibility for road monitoring and control remains with the driver. In terms of hardware configuration, the foundational framework of Tesla autopilot relied upon an integration of cameras, RADAR, and ultrasonic sensors to establish an environmental understanding. Cameras were instrumental in object recognition, including vehicles, pedestrians, and cyclists. RADAR, on the other hand, extended perception to distant entities such as vehicles on highways. The ultrasonic sensors played a role in detecting proximate objects like curbs and obstacles. However, a notable shift has been observed from 2021 onwards, where Tesla cars transitioned to sole reliance on Tesla vision, a camera-based autopilot system. The neural network constitutes the heart of Tesla autopilot, processing sensor data and rendering driving decisions based on an extensive training dataset. Presently offered in three tiers, the software's pinnacle variant, full self driving (FSD), facilitates urban driving and automated control at intersections and stop signs.

Toyota e-Palette is a concept car that was released in 2016. It is designed to be used as a self-driving shuttle or delivery vehicle and is equipped with a variety of sensors, including cameras, RADAR, and LiDAR, which allow it to perceive its surroundings. The car also has a powerful computer that can process the sensor data and make decisions about how to drive. Toyota e-Palette is designed to be fully autonomous and does not require a human driver to be present.

Cruise, an autonomous vehicle company headquartered in the United States, was founded in 2013 and subsequently acquired by general motors in 2016. Following this acquisition, the firm has been earnestly involved in crafting specialized software for general motors' Chevrolet Bolt, with the overarching objective of bestowing the vehicle with autonomous capacities. Facilitating this transition, the Bolt incorporates an ensemble of LiDAR sensors procured from Velodyne. A noteworthy milestone was achieved in January 2020, with the debut of the Origin—an entirely autonomous electric vehicle distinguished by its unique lack of steering wheel and pedals. This pioneering design propels the electrical vehicle (EV) into the realm of level 4 autonomy, potentially accommodating level 5 functionality within specified regions. Particularly notable is the symmetrical internal configuration of the origin, featuring two sets of opposing seats, accentuating its suitability for highway travel. Delineated by its modular construct, the vehicle touts a projected lifespan of one million miles, a remarkable advancement sixfold greater than conventional automobiles. The vehicle's intended role as a ride-sharing taxi within Cruise's exclusive service framework precludes personal ownership. Augmenting the travel experience, digital overhead displays provide essential information to occupants. Elevating perceptual capacities, the vehicle integrates an innovative 'hybrid sensor assembly' known as 'owl,' seamlessly amalgamating camera and RADAR functionalities.

Zoox self-driving car (2018) is a self-driving car company that is developing a fleet of autonomous taxis. Their cars are designed to operate in dense urban environments. The cars are electric and have a round design, which allows them to navigate tight spaces. Zoox has been testing its cars in Las Vegas, Nevada. They are designed to be fully autonomous and to not require a human driver. It is equipped with a variety of sensors, including cameras, RADAR, and LiDAR, which allow it to perceive its surroundings in 360 degrees. The car also has a powerful computer that can process sensor data and make decisions about how to drive safely and efficiently while still in the development stage, but the company has already logged over 1 million miles on public roads. They are currently testing their cars in Las Vegas, Nevada, and they plan to launch a commercial service soon. Nuro R2 (2018) is a self-driving car that is designed to deliver goods. The car is small and has no steering wheel or pedals. It is designed to operate at slow speeds and in areas where there are few pedestrians or other vehicles.

Nuro has been testing its cars in Houston, Texas, and is still in the development stage with over 100,000 miles on public roads logged. Aurora self-driving truck (2019) is a self-driving car company that is developing a platform for autonomous trucking, their platform is being used by several trucking companies with more than 1 million miles on public roads.

Argo AI is dedicated to the comprehensive advancement of an integrated autonomous driving system, with a particular emphasis on its potential for ride-sharing and goods delivery applications. Strategic partnerships with prominent automotive manufacturers like Ford and Volkswagen underscore the company's steadfast commitment to this trajectory. Argo AI's core objective centers around the progression of level-4 automation technology, a categorization emblematic of its substantial autonomy in driving operations. A fundamental dimension of this undertaking entails the development of an all-encompassing product, spanning both the software platform and an array of sensors, encompassing elements such as LiDAR, RADAR, and cameras. Augmenting this approach, the ARGO AI's toolkit incorporates an autonomous vehicle platform, thoughtfully adapted from conventional tools to facilitate vehicle control through computer-generated directives. In its pursuit of addressing challenges tied to perception and decision-making, Argo AI strategically amalgamates machine learning algorithms with deep networks to navigate intricate problem domains. The real-world testing phase involves the deployment of Ford Fusion Hybrid vehicles, with a notable exploration into the evolution of goods delivery vehicles in urban settings. In June 2019, a valuable alliance was formed between Argo AI and CMU, marked by a robust five-year collaboration valued at $15 million for research. This joint venture is recognized as the "CMU Argo AI center for autonomous vehicle research," and its focus is primarily on the progression of algorithms specifically designed for autonomous vehicles. Argo AI has cleverly structured fail-safe systems for vital operations such as braking, steering, and power distribution to guarantee an elevated level of safety. This design guarantees a seamless transition to backup systems in scenarios involving power loss. These provisions factor in the potential failure of a vehicle's 12-volt power system, wherein traditional vehicles can be brought to a halt through manual brake pedal application. Argo AI's implementation involves the establishment of auxiliary electrical power sources for key components. In cases of system malfunction, these components, ranging from computers and sensors to braking and steering systems, are equipped with low-voltage power reserves to facilitate vehicle halt.

In 2015, news emerged about Apple Inc.'s venture into the automobile sector, a project termed as "Project Titan," which signaled a significant shift from its established consumer electronics business. The anticipated vehicle, frequently referred to as the "Apple Car," is predicted to represent the future of transportation, with a focus on automation, connectivity, and green energy. Although many specifics about the project are yet to be revealed, it is believed that the car will benefit from Apple's substantial skills in software hardware integration and its well-known proficiency in user interface design. The primary objective appears to be the creation of a cutting-edge self-driving system, mirroring the industry's ongoing movement toward autonomous vehicles. Furthermore, Apple's transition towards the production of electric vehicles aligns with its environmental goals, as outlined in its 2020 environmental progress report. However, the realization of project Titan is contingent on numerous factors, such as securing the necessary regulatory permissions, establishing manufacturing capabilities, and achieving market acceptance. Despite the potential challenges, the Apple car signifies the possible amalgamation of technology and transportation, which has the potential to fundamentally redefine the automotive industry.

7. CONCLUSION

The field of autonomous vehicles is undergoing a progressive transformation, characterized by advanced levels of automation and enhanced safety mechanisms. The pursuit of integration with intelligent urban infrastructure, as well as the implementation of vehicle-to-everything (V2X) communication and AI, infused decision-making frameworks, is currently underway. The industry's trajectory is set towards the attainment of Society of SAE autonomy levels 4 and 5, which denote a minimal to non-existent requirement for human oversight. This evolutionary journey of autonomous vehicles is incremental, underscored by significant strides in technological innovation, concerted research efforts, and an escalating receptivity towards autonomous vehicular technologies within the automotive sector. As we progress, it is anticipated that ongoing advancements in AI, sensor technologies, and regulatory architectures will persist in delineating the trajectory of autonomous vehicular transport. Nevertheless, there remain several impediments that must be surmounted before the ubiquitous adoption of autonomous vehicles, including the refinement of sensor systems and algorithms capable of adeptly and safely maneuvering through intricate environments, such as urban thoroughfares. Despite these challenges, the advancement of autonomous vehicles is advancing with alacrity. It is projected that self-driving vehicles will transition from concept to reality soon, harboring the potential to fundamentally transform the domain of transportation. Autonomous vehicles stand to enhance road safety, diminish traffic congestion, and ameliorate air quality. Moreover, they hold promise in augmenting transport accessibility for individuals who are presently unable to operate vehicles, including the elderly and individuals with disabilities. The advent of autonomous vehicles represents an exhilarating epoch in technological development, one that holds the potential to effectuate substantial impacts on our daily existence. We find ourselves on the precipice of a novel era in transportation, where we are yet to see how autonomous vehicles will sculpt the future landscape of mobility.

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