Extensive Tests of Autonomous Driving Technologies

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***Abstract*—This paper presents the vision of the Artificial Vision and Intelligent Systems Laboratory (VisLab) on future automated vehicles, ranging from sensor selection up to their extensive testing. VisLab's design choices are explained using the BRAiVE autonomous vehicle prototype as an example. BRAiVE, which is specifically designed to develop, test, and demonstrate advanced safety applications with different automation levels, features a high integration level and a low-cost sensor suite, which are mainly based on vision, as opposed to many other autonomous vehicle implementations based on expensive and invasive sensors. The importance of performing extensive tests to validate the design choices is considered to be a hard requirement, and different tests have been organized, including an intercontinental trip from Italy to China. This paper also presents the test, the main challenges, and the vehicles that have been specifically developed for this test, which was performed by four autonomous vehicles based on BRAiVE's architecture. This paper also includes final remarks on VisLab's perspective on future vehicles' sensor suite.**

***Index Terms*—ADAS, autonomous vehicles, HMI, robot navigation, sensor integration, vision-based guidance.**

I. Introduction

DRIVERLESS vehicles will be a reality in the few next years and will reshape the future mobility of people and goods. Currently, a large number of research centers are working on defining the sensing suite, perception algorithms, onboard intelligence, control architectures, and communication layers that will likely constitute the basics of our future vehicles.

Even more important than the definition and development phases that are previously mentioned is the testing phase, since it is required to finally validate the whole system and must be undertaken in realistic conditions. Therefore, extensive and possibly exhaustive tests must be run on real roads to expose the vehicles to the largest set of real scenarios and challenge all their subsystems with different behaviors.

The Artificial Vision and Intelligent Systems Laboratory (VisLab) research group, which has been active in this field for years, developed many different perception modules that were installed on different vehicle prototypes. The underlying approach that has always been driving VisLab's research is summarized in the following two keywords: low cost and deep integration. The perception layer (sensors and algorithms) that has been integrated on the different vehicle platforms has been deployed with those criteria in mind. Cameras were preferred to more sophisticated and invasive sensors such as 3-D LIDARs; the cameras' low cost and very straightforward integration options make them the perfect candidate for integration in future series vehicles.

All VisLab perception systems (the ones integrated on ARGO [1], TerraMax [2], BRAiVE [3], and the VisLab Intercontinental Autonomous Challenge (VIAC) vehicles [4]) are primarily based on vision; TerraMax was the only vehicle that reached the end of the Defense Advanced Research Projects Agency (DARPA) Grand Challenge [5] with vision as its primary sensing technology.

The importance of extensive testing has been always perceived as a hard requirement to validate the results, and a large number of tests have been organized and carried out on those vehicles. The first one, which is called "MilleMiglia in Automatico" [6], involved driving more than 2000 km on Italian highways with the ARGO vehicle; this pioneering effort, which was organized in 1998, marked the history of driverless cars. Indeed, the DARPA challenges played an important role in testing since the teams stressed their vehicles for thousands of kilometers before the races. After the two challenges, the DARPA stopped its involvement, and it was only due to the entrepreneurism of a few research centers that other more specific tests were organized. High-speed car control was tested by Stanford [7], who ran the Pikes Peaks rally drive; autonomous operations in real scenarios were targeted by many others like Google [8], Braunschweig University [9], and Berlin University [10]. Cooperative driving was the main objective of the Grand Cooperative Driving Challenge [11], which involved a large number of teams [12]–[14], such as the Karlsruhe Institute of Technology [15].

VisLab also felt the need to organize an extended test of their vehicles; this paper presents VisLab's latest prototypes based on a low-cost and highly integrated sensing suite, as opposed to the other vehicle implementations that are previously mentioned, and describes the unique test performed in 2010, when four electric and driverless vehicles drove from Parma, Italy, to Shanghai, China.

This paper is divided as follows. Section II presents the BRAiVE vehicle and the low-cost solutions that are adopted to make it a clean and very integrated demo vehicle. Section III describes the functions that are implemented on BRAiVE. Section IV motivates the need for a long test, while Section V presents the new vehicles that were developed just to run this test. Section VI describes the main challenges in

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Fig. 1. BRAiVE prototype.

the organization of an intercontinental test, while Section VII summarizes the main results. Section VIII concludes this paper with some indications on the future steps on which VisLab will be involved, and this paper's conclusions are summarized in Section IX.

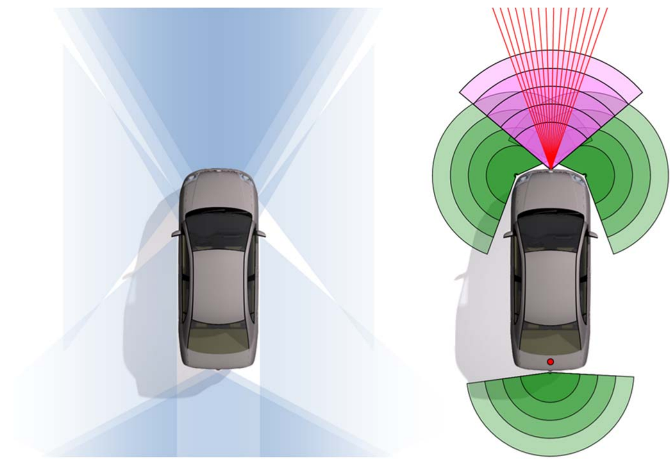
II. BRAiVE

BRAiVE, which is short for brain drive (see Fig. 1), is an autonomous ground vehicle that is designed with the aim of being a platform for developing, testing, and demonstrating advanced safety applications with different automation levels. This includes the development of driving assistance systems, such as traffic-sign recognition [16], [17], lane-keeping assistant [18], [19], collision warning [20], adaptive cruise control [21], and fully autonomous driving behaviors, such as GPS waypoint following [22] and vehicle following [23]. BRAiVE has been built on top of a Hyundai Sonata by integrating all the technologies and technological achievements that have been learned in the field during VisLab's 20 years experience.

The vehicle is being used as an *advanced driver-assistance system (ADAS) development platform*, exploiting the knowledge VisLab has acquired on a wide variety of intelligent vehicle prototypes; the rich sensor suite can be partitioned to develop different applications in the field of intelligent vehicles (e.g., pedestrian detection, obstacle detection, vehicle following, collision warning, traffic-sign recognition, parking-lot detection, backup maneuver, collision detection, etc.). Plus, all algorithms can be concurrently combined and executed to provide increased levels of automation, up to fully autonomous driving.

BRAiVE's unique integration makes it a perfect *technology demonstrator* since all sensors are deeply integrated and most of them are invisible. Special care was put in positioning sensors and control units, and cables run hidden so that the vehicle looks just as a normal car that is delivering superior guests' experiences.

BRAiVE's cabin is divided into three separated areas corresponding to the following three main purposes of this prototype: 1) development; 2) test; and 3) demonstration. The front passenger seat is used for *code development and tuning*; a 17-in touch screen is mounted in front of the passenger seat, together with a Bluetooth keyboard and a mousepad that is integrated in the internal door handle. All equipment has been designed to be easily removed (or made invisible) during demonstrations so that the internal part appears like a normal vehicle.



(a) (b)

Fig. 2. Coverage of (a) vision and (b) laser sensors.

The driver seat is used for *testing*; the driver has the ability to interact with the vehicle due to an infotainment-like touch display, which is placed in the middle of the dashboard. A view of the controls and the displays that are available from the front seats is shown in Fig. 7. The rear seats, as shown in Fig. 8, are used to host guests for *demonstrations*; two 8-in monitors are integrated in the back of the head rests for the convenience of rear passengers. They can either replicate the output of the front monitor or show only high-level information such as a synthetic female face describing the vehicle's decisions and maneuvers.

The platform is composed of Sensing, Processing, Actuation and X-By-Wire, Power system, and Safety system. All these layers are described in the following sections.

A. Sensing

BRAiVE's sensing suite is based on 10 cameras, 4 laser scanners, 1 radar, 16 fixed laser beams, and a GPS and inertial measurement unit (IMU) system. Although sensors are mounted all around the vehicle to obtain a 360° all-round coverage, they are mainly concentrated in the frontal area, with four cameras, four laser devices, and a radar, all pointing forward. Sensors' coverage areas are shown in Fig. 2. It is very important to note that BRAiVE integrates a large number of sensors with overlapping fields of view and even redundant sensors, the main reason being the possibility of testing different combinations of sensors and technologies as a traditional laboratory (see Fig. 3).

- *Cameras:* Ten firewire A cameras are mounted all around the vehicle, i.e., four in the frontal part, behind the windshield, looking forward; two over the front wheels, looking sideways (see Fig. 4); two in the external rear-view mirrors facing backward (see Fig. 5); and two installed over the license plate looking backward (see Fig. 6).
- The cameras that are integrated in the mirrors are PointGrey FireFlyMV, based on the Aptina MT9V022 752×480 pixel sensor. The other cameras are PointGrey Dragonfly2, based on the Sony ICX 204 and 424 1296×964 pixel sensor.
- All cameras are connected to the boot through firewire cables for data exchange, while another cable provides additional signals such as triggers for synchronization.

Fig. 3. Detail of the vehicle front. The Hokuyos UTM-30LX are installed on the sides, the IBEO Lux is installed in the center of the bumper, and the Hella IDIS on top of it.

Fig. 4. Detail of one of the lateral cameras.

The set of cables reaching the boot can be reconfigured and connected to different computers, depending on the application requirements.

- *LIDARs:* Five LIDARs are mounted around the vehicle. They belong to three different categories, i.e., three single-plane Hokuyo UTM-30LX units, a four-plane IBEO Lux unit, and a 16-beam Hella IDIS unit; while the first two types are regular laser scanners with a mechanical technology based on a rotating mirror, the last one does not contain moving parts and the 16 beams are stationary. Each category has been selected due to both its perception capabilities and its integration level. All the LIDARs have been integrated into the vehicle body with the aim of reducing the impact on the car design; the only exception is the position of the Hokuyos, whose required field of view imposes an installation leaning out of the car's chassis. The three Hokuyos guarantee a short-range safety area, covering all the surroundings of the vehicle; they are mounted 50 cm above the ground: one on each front bumper corner (see Fig. 3) and one in the middle of the rear bumper (see Fig. 6); their aperture is 270°, while their detection range is around 20–30 m, depending on weather conditions. Since these devices are targeted for indoor robotics, some performance degradation has to be expected under strong sunlight conditions. Each of them is linked to a Universal System Bus (USB) hub in the boot through a USB 2.0 connection.

Fig. 5. Detail of one of the cameras mounted in the rear-view mirror.

Fig. 6. Detail of the back of the vehicle. A stereoscopic camera system is integrated over the license plate. A single Hokuyo UTM-30LX laser scanner is integrated in the center of the bumper. One of the original parking-aid sensors was lowered.

- The IBEO Lux is a relatively small automotive grade unit; its horizontal aperture is 110°, and its detection range reaches 80 m in good weather conditions. BRAiVE hosts this unit in the middle of the front bumper (see Fig. 3).
- The Hella IDIS unit is mounted over the IBEO Lux, again in the vehicle's center, and integrated into the external part of the radiator grill (see Fig. 3). This single-plane unit has 16 fixed laser beams, each of which being separated by 1°; considering the average remission of obstacles, detections can be considered reliable up to approximately 110 m in good weather conditions.
- *Radar:* A universal medium range radar (UMRR) 24GHz Stop&Go Radar from Smart Micro Wave Sensor has been installed on the left side of the front part, behind the bumper. The radar is connected via controller area network (CAN) to an electronic control unit (ECU) that processes the raw data and returns a list of tracked objects as output, also supplying their speed information.
- *GPS and IMU:* A small GPS antenna is placed on the top of the boot cover and is connected to a RaceLogic VBOX-2 GPS receiver and logger, which is hosted in the boot. An IMU again by RaceLogic is placed in the cabin, under the central tunnel, to measure the vehicle inertial status. Close to the IMU, an additional yaw rate sensor by Mando provides further and more accurate inertial measurements.

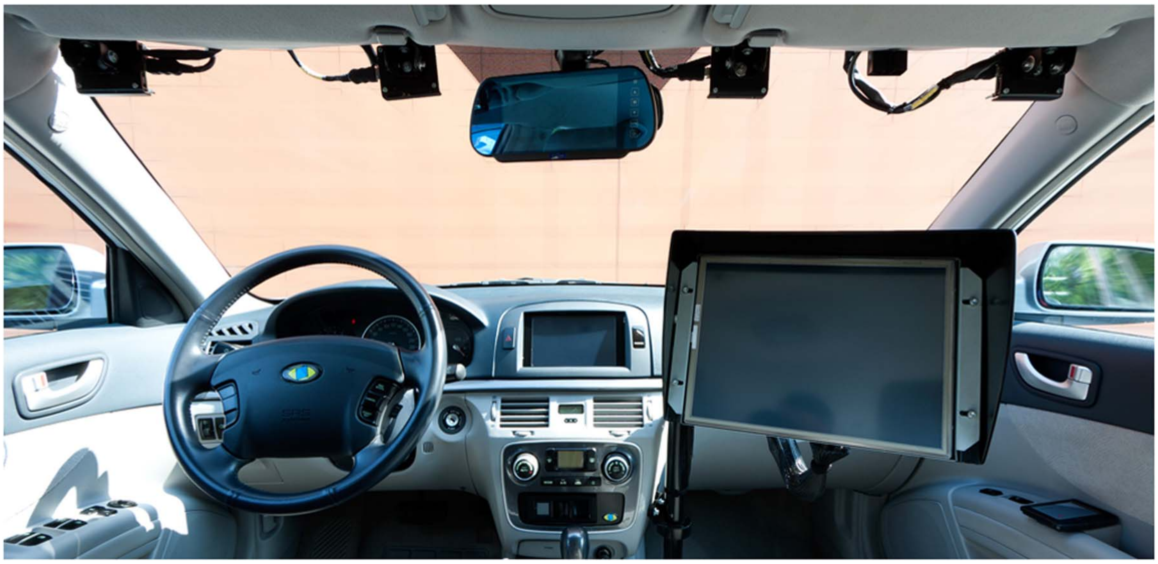


Fig. 7. View of the front seats and equipment.

Fig. 8. View of the rear seats with the demo monitors and the power plug on the central tunnel.

Other information, such as odometry, vehicle status, and human machine interface (HMI) commands, is also available via the car CAN bus to complete the perception layer.

B. Processing

All sensors and actuators are connected by means of their specific interfaces (such as firewire, USB, CAN, and Ethernet) to the appropriate controller hosted in one of three computers placed in the boot. All three computers have the same conservative features: Intel Core 2 Duo, 2.6 GHz, and Mini-ITX industrial motherboard with an automotive designed aluminum case that has been customized for this specific purpose. Due to a simple interconnection topology, the system can be easily reconfigured to gather and process data from different sets of sensors.

During the last 15 years, VisLab has been developing GOLD [24] (the original meaning was General Obstacle and Lane Detection), which is a tool for rapid algorithm development, implementation, and assessment for automotive applications. GOLD can acquire data from multiple sensors with or without synchronization, allowing the easily development data-fusion-oriented algorithms. It offers an abstraction layer over real devices to free the programmer from the burden of performing low-level hardware management, whereas high-level applications are built as independent plug-ins. To support programmers in the implementation of vision-based algorithms, the GOLD framework provides low-level image-processing functions that allow preprocessing acquired data performing common operations (such as image stabilization or distortion removal) and sharing the results among all the active plug-in applications. Moreover, it includes a graphical user interface that allows programmers to interact with applications, independently of available graphic back ends [25].

The functionalities described in Section III are implemented as applications of the GOLD software, which, as of today, consists of about 150 000 lines of C++ code.

C. Actuation and X-By-Wire

The X-By-Wire system that is installed by Mando is made of three actuators, i.e., one for the steering wheel that is a modified electrical power system (EPS) electronic stability programme (ECU), one for the gas that is an X-By-Wire accelerator, and one for the brakes connected to the ESP. All the actuators are controlled through CAN messages that are sent on a dedicated CAN bus branch that is connected to a dSpace Micro Autobox. Results of environmental data are properly packed in a train of CAN messages that are targeted to the high-level actuation layer and sent to the Micro Autobox. The Micro Autobox controller translates these messages in an actuator specific format, taking into account the actuator status, capabilities, and requested setup values. Following VisLab's original goal, the X-by-Wire system is invisible to the user, having integrated all ECUs and actuators under the hood (see Fig. 7).

D. Power System

The custom power system includes an additional 100-Ah battery to provide the necessary current to all devices such as sensors, computers, displays, and hubs. The actuators are connected to the main power system. When the engine is off, the auxiliary system can be recharged through a marine grade power supply connected to an external power plug. When the car key is in "accessories" position, the two systems are connected. In this way, when the engine is on, the alternator recharges the auxiliary system, and when the engine is off, the main system can be recharged through a power outlet. Each device can be turned on and off using a custom-built keypad. Whenever a device is absorbing current, the light on the corresponding key is turned on. A main switch located on the keypad allows completely switching off the system (see Fig. 8).

E. Safety

Brakes and gas can be overridden acting on pedals, while to override the autonomous steering system, the driver needs to provide a torque that is higher than the one set by the autonomous system. Therefore, a weak steering-wheel torque that is provided by the system would allow an easy and comfortable overriding possibility, at the cost of a slower movement. Thus, to have quick and reactive maneuvers, it was preferred not to use weak torque values but rather to include additional devices to secure safety. The HMI can be used to switch the system back to manual driving. A further safety level is reached when manually moving the gear from D to N, i.e., completely detaching the autonomous system. Furthermore, a remote radio-based e-stop system is included as an additional safety system when testing without driver on board; the remote control periodically sends a heartbeat to the on-board system and an emergency stop is triggered whenever the heartbeat is not received or when the remote control is manually activated.

III. BRAiVE Functionalities

This section describes the basic perception capabilities that are available on BRAiVE, as well as their combination into functions and behaviors.

A. Perception Capabilities

1) Traffic-Sign Recognition: A wide literature is available on this kind of system, and some car manufacturers already provide this ADAS on their products. The system that is described in [26] has been under development since 2007 and is capable of recognizing all the Italian traffic signs from an image taken by one of the four forward-looking cameras; traffic signs can be detected and recognized in less than 100 ms.

2) Obstacle Detection: The perception of obstacles is obtained using both vision and lasers; while laser technology provides direct obstacle presence and precise distance estimation, vision provides an indirect measurement. Vision-based obstacle detection employs a stereo system [27]; a dense disparity map that is based on semi global matching provides a 640×480 point cloud every 100 ms, which is processed to locate forward obstacles. A replica of this system provides rear-looking obstacle detection and is designed to be used during maneuvers. The cameras, which are integrated in the boot cover and oriented downward, use wide-angle optics to cover a 10×10 m area surrounding the back of the car [28].

3) Lane Detection: Road lanes can be detected due to two different approaches, i.e., monocular [29] and stereo [30].

Images that are captured from one of the four forward-looking cameras are transformed through inverse perspective mapping, and lines are searched for. The stereo-based Lane Detection offers better performance due to the use of 3-D info and obstacle detector for a more robust distance estimation. This system provides a description of the lanes positions as output, as well as a lane marking classification; it distinguishes between solid and dashed lines, and between white and yellow lines. The system can also accept input from other sensors, such as IMU and obstacle detectors, to refine its result.

4) Terrain Mapping: Starting from the same point cloud that is generated for obstacle detection, the terrain profile is generated [31]. This analysis is suitable for off-road driving in absence of lane markings, and it can be also used to estimate the terrain slope when driving on road. Data fusion with one or more laser scanners may refine slope estimation.

5) Vehicle Detection: Vehicle detection fuses data coming from one of the four front-looking cameras and, optionally, lasers. Image features such as symmetry and rear lights are used to locate candidates in the image, while lasers provide accurate distance measurements. Front vehicles are tracked also during sharp curves due to the wide angle that is offered by laser scanners. A version using only vision and fixed laser beams is also available as a lower cost and lower impact alternative.

6) Oncoming-Vehicle Detection: Oncoming vehicles during night driving are detected based on a time analysis of blob movements. The system classifies white blobs with the aim of removing fixed light sources such as reflections from traffic signs and street lights [32].

7) Blind-Spot Monitor: Blind spots in the adjacent lanes are monitored through the cameras that are integrated in the rear-view mirrors, and overtaking vehicles are detected prior to lane change maneuvers. Vision provides a very robust result; therefore, laser data are not fused.

8) Parking-Lot Detection: The 2 lateral cameras (one looking left and one looking right) are used to reconstruct a 3-D profile of parking lots and locate free spaces with high precision (less than 10 cm). The 3-D reconstruction is realized using motion stereo. Unlike sonar sensors, this system is particularly suitable for all kinds of parking lots, i.e., perpendicular, diagonal, and parallel.

9) Scene Classification and Tunnel Detection: This plug-in uses images captured from a single forward-looking camera to classify the current driving scene among downtown, highway, and country depending on the specific image features, due to a classifier based on support vector machines. This application is used to drive other functions by selecting different sets of parameters, depending on the environment.

10) Pedestrian Detection: A new approach for pedestrian detection was developed and extensively tested on the vehicle.

The scenario-driven pedestrian detection system [33], [34] is based on the idea of focusing the search for pedestrians on specific dangerous areas instead of searching in the whole area in front of the vehicle and, at a later stage, to assess the danger. The environment is processed using the data of the frontal laser scanner, and computer vision is then used to validate the presence of a pedestrian. The goal of the system is to detect pedestrians that are suddenly appearing in front of the vehicle, trigger a warning to the driver and, eventually, to brake.

B. Functions and Behaviors

1) Lane Departure Warning: The application interacts with the on-board audio system giving a positional audio feedback to the driver whenever the car crosses or is about to cross a lane marking and direction indicators are not in use. Lane detection, together with vehicle status data (e.g., steering-wheel position and speed), is used.

2) Lane Keeping: Precise and stable lane marking detection is also used for lane keeping. The steering wheel is controlled with the objective of keeping the vehicle centered in the current lane.

3) High-Beam Assist: High beams are automatically switched on and off according to the presence of oncoming traffic during night driving.

4) Stop and Go: High-level actuation capabilities are available trough this function based on Vehicle Detection and Lane Detection. The vehicle automatically keeps a safe distance from the vehicle in front and stays in the current lane. This basic functionality offers full vehicle automation when driving at slow speeds (up to 50 km/h). Special care was put to avoid abrupt maneuvers and speed changes.

5) Emergency Braking: A driving assistant system for braking whenever an obstacle suddenly appears on the vehicle trajectory has been implemented [35]. In case a dangerous situation, e.g., a pedestrian crossing in an unsafe way, is detected, an emergency braking is triggered. During the emergency braking the vehicle is stopped by decreasing the speed at a rate of $-4.0\ \mathrm{m/s}^2$.

6) Waypoint Following: This application allows moving the vehicle through a set of GPS waypoints. A GPS waypoint is an absolute location of a point on earth, and a sequence of waypoints defines the desired path that vehicle has to follow. The application controls the steering wheel, the brakes, and the throttle to complete this goal [36]. The system acts on the steering-wheel setting the desired vehicle heading to minimize the vehicle lateral displacement. Several algorithms run to provide a safe speed (i.e., speed limit, radius of curves, and distance to obstacles) information. The effective speed set point is the lowest of them.

7) Obstacle Avoidance: This functionality takes as input the obstacle detector capability result and interacts with the path planner to elaborate a suitable path for the vehicle to avoid obstacles. The system, which is capable of dealing with both static and dynamic obstacles, is based on penalties that are proportional to the distance between the obstacles and the trajectory itself [36].

C. Fully Autonomous Driving

Due to all the previously described perception and actuation modules, BRAiVE is capable of completely autonomously driving in simple environments. Obstacles, lanes, and vehicles are detected using the sensing capabilities that are previously described. A path planner [36] sets the path to follow, depending on sensed information and on the selected objective, such as following a vehicle or driving along a prerecorded GPS path.

Among the many tests and demonstrations that were organized in the last few years, one of them deserves mentioning; in 2009, the vehicle drove in Rome from Campidoglio through a narrow path with curves and crossing pedestrians toward the Colosseum in leader–follower configuration. Although successful, this test showed the need for deeper and longer tests; all vehicular robotic tests worldwide conducted so far where strictly limited in time and conditions (in terms of infrastructure, traffic, weather, and light). To fully assess the technological capabilities and extend the testing beyond the usual limits, VisLab planned a longer and hopefully exhaustive new test covering different kind of paths, terrain, weather, and traffic situations.

IV. Long Test

A wide variety of tests have been performed on BRAiVE, all yielding fully satisfactory results, but as mentioned, all of them were limited in time; most of them were organized in specifically structured scenarios, others in predictable environmental conditions—in other words, friendly conditions such as the DARPA Urban Challenge [37]. Further tests in similar environments would have brought limited advantages, since the most important factor that needs to be tested is the system ability to cope with a plethora of different and unpredictable scenarios, i.e., the real world.

Therefore, to stress BRAiVE's perception system, VisLab organized a huge experiment that had never been conceived before. The test had to be extensive (more than one month of continuous operation), hit different scenarios (including road infrastructures, weather conditions, illumination conditions, road and off-road, and rural and urban traffic patterns), and involve driving on real roads with the final goal of detecting faulty situations of the perception system.

The longest distance on the ground (i.e., with no water crossing) that can be covered leaving from Parma, Italy, is reaching the eastern part of Asia. Since, in 2010, the World Expo was in Shanghai, China, VisLab decided to challenge its autonomous driving technology with a three-month long trip crossing Europe to Asia with the final goal of reaching the World Expo and showcasing its technology to the world.

To make it a very unique challenge that could also provide a vision for future mobility, VisLab chose the Piaggio Porter Electric as vehicle platform for the challenge (see Fig. 9); thus, the VIAC also became an extensive test for electric vehicle technologies. Although in a simplified and prototypal version, the test showed that, in the future, it will be possible to move goods between two continents in a fully sustainable way with electric vehicles using green energy and with no driver on board.

Fig. 9. One of the VIAC vehicles that reached Shanghai.

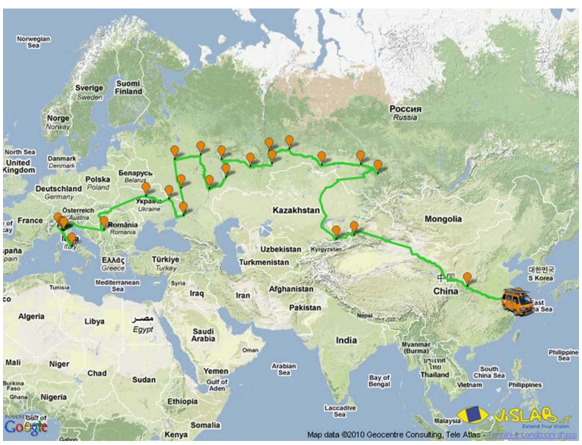


Fig. 10. Route covered by VIAC as it was available in real-time on VisLab's Web site during the trip: more than 13 000 km from Italy to China.

VisLab then gave birth to the VIAC, which is a 13 000-km-long test of autonomous driving technologies along a totally unknown route crossing Europe and Asia (see Fig. 10); it was the longest ever test of driverless cars in robotics history [38]. Throughout the journey, the expedition traveled across a plurality of completely different scenarios; by crossing a large part of the Eurasian continent, all sorts of situations, environments, roads, and weather conditions were met (see Fig. 11). The VIAC was a huge experiment that aimed at testing VisLab's state-of-the-art perception.

Although aiming at reaching the 2010 World Expo in fully autonomous mode, the end of the event on October 31, 2010, and the long delays in crossing the various customs offices made it necessary to run part of the Chinese route in manual mode to catch up with the schedule.

V. VisLab Intercontinental Autonomous Challenge (VIAC) Vehicles

To extend the daily covered distance and to allow for backups, four identical vehicles were realized by replicating the original design. Aside from an increased cost, this choice also caused the need for additional time for implementation, testing, and maintenance. However, most of the sensing technology that is installed on the vehicles was already available since it is directly derived from BRAiVE perception suite. Nevertheless, BRAiVE was not designed to drive in off-road environments; hence, it lacks all the cross-country driving skills that are needed in an intercontinental trip such as the VIAC. The sensor layout was therefore revisited, and new algorithms were incorporated to handle off-road scenarios. Another key difference with the BRAiVE sensing suite is the physical placement and wiring of sensors: on BRAiVE all sensors and cabling were hidden, all actuation devices were installed below the hood, and special care was taken to provide the car with a clean and tidy look. The VIAC vehicles have been instead equipped keeping sensors, actuators, and processing units that are accessible and easily reachable to optimize development time, improve usability, and facilitate maintenance in remote locations. As shown in Fig. 9, most of the sensors were mounted outside the vehicle and were easily reachable, but unfortunately, they were also exposed to any kind of weather condition.

The traction electric circuits were kept separated from VisLab's customized ones, the latter being powered by a solar panel mounted on the roof, thus leaving the original capacity of the 16 traction batteries intact. The only potential performance penalty with respect to the original design was the additional weight of the custom hardware, which is, in fact, neglectable if compared with that of the vehicle itself (the batteries alone weight 450 kg).

The following subsections provide a comparison between the VIAC vehicles and BRAiVE's sensors, processing, actuation, and safety.

A. Sensing

Special emphasis has been given to computer vision technology since it provides a *cost-effective* way of sensing the environment. No particularly expensive sensors have been considered in the design, and no sensors with special needs in terms of physical installation have been included, just like what happened for BRAiVE. A clear advantage of vision is that cameras can be installed *in a variety of positions* on the vehicle (inside the cabin, on the roof, and inside the headlights), while laser scanners used for mid-/long-range sensing need to be placed in front of the vehicle and are usually integrated into the front bumper. This constraint increases the chances that laser scanners are hit by rocks, debris, and other objects on the road, particularly when driving off-road; therefore, a bull-bar was also installed.

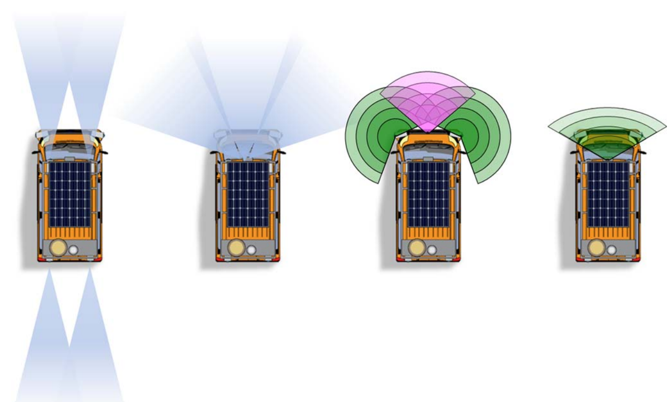
A total of seven Point Grey Firefly cameras (five forward and two backward-looking) and four laser scanners with different characteristics were installed on each vehicle, as shown in Fig. 12. In particular, each vehicle is equipped with the following sensors.

- *Front and Back Stereo Cameras*: Two stereo systems are used to locate obstacles, estimate terrain slope, and locate lane markings. The baseline is about 80 cm; they are used for short- to medium-range sensing.

(a) (b) (c) (d)

Fig. 11. Examples of different scenarios met during the test. (a) Rain, (b) night, (c) off-road, and (d) shadow.

- *Panoramic Vision System*: It provides a nearly 180° horizontal view of the frontal part of the vehicle by stitching images coming from three synchronized cameras. The resulting image is a high-resolution (752 × 480) frontal view that is used to detect and track the leader vehicle even when approaching a tight curve or a steep hill.
- *Lateral Laser Scanners*: Two single-beam Sick LM151 laser scanners are mounted on the corners of the frontal bumper; they are used to detect obstacles, pedestrians, and vehicles in the immediate surroundings. Each laser scanner has an aperture of about 270°, while their perception depth is about 30 m.
- *Central Laser Scanner*: A four-plane Sick LD-MRS laser scanner is used to detect vehicles, obstacles, and pedestrians in front of the vehicle. Its four planes allow partially overcoming false detections that are caused by vehicle pitching. Its perception depth is about 80 m, and its aperture is about 100°;
- *Off-Road Laser Scanner*: This single-beam Sick LMS111 laser scanner is pitched down so that the beam hits the ground roughly 5 m in front of the vehicle; it provides information about the presence of ditches berms, bumps, and obstacles right in front of the vehicle. It was specifically integrated to handle off-road driving.
- *GPS, IMU, and V2V radio*: The control system takes advantage of the information that is provided by a TopCon AGI3 unit: an inertial and geolocation device installed on the vehicle roof. Gyroscopes show a noise level less than 0.03 rad/s at working temperature. Both systems provide their information at a 20-Hz rate.



(a) (b)

Fig. 12. (a) Vision and (b) laser scanner sensors placements. From top to bottom: Front and rear stereo cameras, panoramic vision system, lateral and central laser scanners, and off-road laser scanner.

B. Processing

The processing units are composed by three off-the-shelf multicore computers, two of which are Intel Core 2 Quad Q9100 2.26 GHz, dedicated to sensing, and the last, which is an Intel Core 2 Duo T8100 2.10 GHz central processing unit, is entirely devoted to planning and control. Communication takes place on a gigabit Ethernet local network on top of a data distribution service. All sensing information provided by sensors is collected, and the surrounding map of the vehicle is generated. Using this map, the path planner evaluates all feasible trajectories and, using the best one, drives the actuators [36].

Fig. 13. By-wire steering system.

C. X-By-Wire

Different devices have been installed to control vehicle speed and steering.

- A servo motor (see Fig. 13), which is provided by TopCon, is directly connected to the steering-wheel column and controlled in position, speed, and torque through CAN bus messages. The set point is internally followed using a proportional–integral–differential controller.
- Speed is adjusted by changing the duty cycle of the pulsewidth-modulation signal that controls the engine through a custom board that is connected to the CAN bus.
- The brake is operated by an electric linear actuator, which directly acts on the brake pedal, and it is controlled via a CAN open interface.

D. Safety

As a safety measure, all actuators (the steering wheel, the braking, and throttle devices) have been designed to be easily overridden by a human driver. Additionally, a radio-based emergency stop is also available.

VI. VIAC Organization

Any *a priori* knowledge and expectations on the set of scenarios that would have been met during the trip would have allowed designing the vehicles' structure and accordingly plan the sensor suite, but unfortunately, it was not possible to have such information. No assumptions were available, contrary to what happened at the DARPA challenges, in which a set of well-defined rules defined the environment and the expected situations that the vehicles had to face. The preparation of the VIAC trip suffered from the lack of three basic assumptions.

- No map was available for most of the trip, making it impossible to design an autonomous route planner. Plus, no GPS coverage was guaranteed throughout the trip.
- No information about the kind of roads was available; therefore, the sensor suite had to include solutions that would have allowed operations in any environment, including urban, freeway, and off-road.
- No assumptions were possible on other vehicles' behavior, contrary to what happened during the DARPA challenges (i.e., other traffic was either static or respectful of traffic rules).

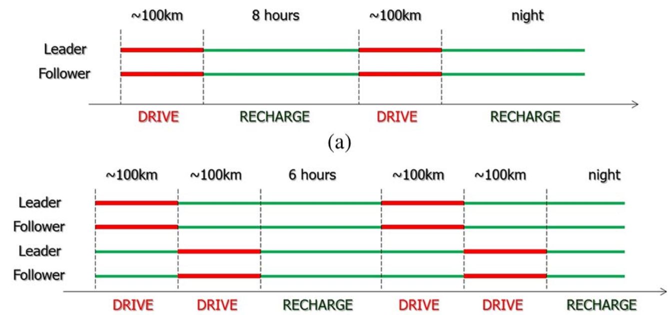


Fig. 14. (a) Driving pattern using only one pair of vehicles. (b) Driving pattern using two pairs of vehicles.

Therefore, since the VIAC's primary goal was to stress the perception technology over a large set of conditions, while fully autonomous driving was a second-level goal, a leader–follower approach was chosen for *autonomous operations;* human interventions on the leader vehicle were necessary to define the route, while the follower was fully autonomous. Vehicle following was possible either by visually locating the previous vehicle or by following its GPS trace sent over a ultrahigh-frequency radio link, when no visual contact was possible. The follower's sensing suite was therefore used to automate its movements, while data recording, which is aimed at studying and improving *environmental perception* once back in laboratory, was taken care of by the leader's sensing suite. During the recording, engineers on-board the vehicle had the opportunity to label the data with keywords to simplify the data access to easily access data segments with specific characteristics. Aside from that, leader–follower, and waypoint following, the trip allowed testing the detection of obstacles, lane markings, vehicles, terrain slope estimation, and other perception subsystems. Being autonomous route planning impossible, only simple behaviors were implemented, such as obstacle avoidance and lane keeping. Long-term path planner was only tested in local demonstration, where a map was available.

Logistics played a basic role as their complexity required additional effort. Not only paperwork had to be prepared and bureaucracy fulfilled (e.g., visas, driving licenses, license plates, and vehicle homologation), but logistics had an impact also on technical operations. As an example, being the electric vehicle's autonomy around 100 km and the recharge cycle around 8 h, the average day would have been covered by one run in the morning (100 km), recharge, one run in the afternoon (100 km), and then recharge during the night. Since this pattern would have required more than three months to conclude the challenge, two sets of vehicles were used, allowing for four runs per day, as shown in Fig. 14.

The drawback of using two pairs of vehicle was that, each day, all vehicles had to be swapped multiple times, a truck was necessary to house the nonused vehicles, and the cost was indeed doubled.

VII. VIAC Data

The test was successful with only minor issues (such as the complete replacement of the battery pack of one vehicle in

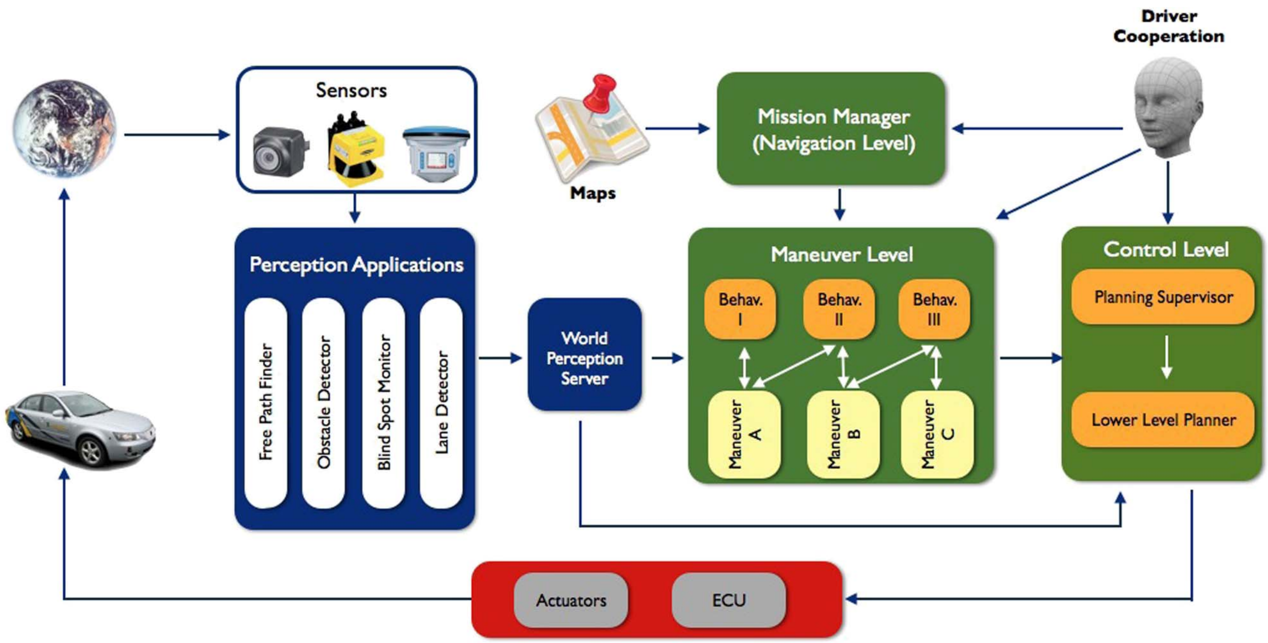


Fig. 15. Description of the system architecture developed due to the results that are obtained in the previous projects.

Moscow). The collected data covers the 61 effective days of autonomous driving, with a total amount of 214 h of operation, divided into 191 different sessions. The maximum distance that was covered in a single run in autonomous mode was 96.7 km (the vehicles had about 100-km autonomy on a single charge). The average speed was 38.4 km/h with a maximum speed of 70.9 km/h. More results and in-depth discussion on control can be found in [36] and [39]; details on sensing requirements can be found in [40], and calibration procedure is described in [41]. Finally, logistics issues are discussed in [42].

During the trip, VisLab engineers fixed some issues in the software, but the real value of the recorded data is the possibility of improving the current sensing algorithms and even designing new ones using a large set of different environmental situations.

Each algorithm that has been tested during the trip showed its own criticality, and developers tried to solve them during the trip itself (it was, in fact, a development trip and not only a test). The vehicle–follower algorithm, for example, was demonstrated to correctly work only with an update rate over 10 Hz, but to evaluate the trajectory in particular conditions (crossing vehicles or overtaking vehicles), an update rate of at least 25 Hz and a field of view of 270° around the autonomous vehicle were necessary.

VIII. Further Improvements

The VIAC project was an excellent opportunity for a deep test of the developed artificial vision algorithms and the vehicles' control system. Discussion on some results is available in [27]; as mentioned in the previous section, the lack of maps did not allow having a long-term plan.

Therefore, after the conclusion of the VIAC project, further research activities have been concentrated on the development of an improved system architecture also including maps and based on different automation levels. It is based on a 360° tensorial suite, which includes perceptual and decision making modules, with the ultimate goal of providing the vehicle with autonomous driving capabilities and/or supervise the driver.

The guidelines of this software architecture are

- use of enriched maps to perform long-term planning;
- multilevel sensor fusion;
- modularity: the sets of sensors, perception applications, and even tasks depend on the specific installation so that the architecture must necessarily have a strong modularity;
- total separation of perception, planning, and actuation;
- introduction of vehicle–driver cooperation;

The key features of this architecture, as shown in Fig. 15, are described in the next sections.

A. *Maps and Long-Term Planning*

The availability of maps allows performing long-term planning (e.g., missions). Maps coming from the Open Street Map project have been imported as they are, with the possibility of adding additional data such as the number of lanes, lane size, road signals. Long-term planning has been divided into three levels, each of which based on a different quantity of information coming from maps and perception.

- **Navigation Level**: At this level, routing information is created as a set of adjacent map segments starting from the current position and heading to the destination. The information involved at this level comes only from maps, and local perception has no influence.
- **Maneuver Level**: Routing information at navigation level is split into a set of actions depending on both maps and local perception information. When moving on a straight road, dynamic information is used to alter the original lane following plan; the presence of an obstacle or a slower vehicle would induce alternative maneuvers to avoid or overtake it or simply adapt vehicle speed.

- **Control Level**: This level performs short-term trajectory planning and actuates the decisions taken at the higher level using only local perception.

For each abstraction level, there will be different modules that can achieve the same goal, as showed in Fig. 15. Each module has a priority value, and at each planning step, the feasible module with the highest priority will be selected: one for each abstraction level; using this approach, we can compute a fast re-planning in case of error, and we can configure trips using high-level parameters.

B. Sensor Fusion and Perception Server

In the literature [43], fusion is defined as the combination or the integration of acquired information to improve the cognition level of the environment. Multisensory fusion can be applied to every system that is dedicated to recover and synthesize information.

The most common sensors in autonomous driving applications are cameras, radar, laser scanners, and positioning systems; they are intrinsically noisy, and the World Perception Server (WPS) component gathers their information and reorganizes it in the form of consistent and complete representation of the world around the vehicle. Sensor fusion techniques are applied not to the information that is directly generated by sensors but to the high-level data that are obtained by information processing; in fact, a low-level fusion is executed within every application, and afterward, a high-level fusion is carried out within the WPS to reconstruct a high-level map of the surrounding environment as most accurate and reliable as possible.

The WPS main features are the following.

- Collection of sensor information: Perception applications acquire data from sensors, process them, and return high-level data describing the perceived environment. All this information must be collected by the WPS.
- Sensor fusion: Data from different sensors are merged together; perceptions of the same object, which are performed by several sensors with different capabilities, are used to create a single object that considers all the information and its evolution over time.
- Publication of the world map: Similarly to perception applications, the WPS has to make the results of its processing available to other modules.

Compared with our previous experiences, these features introduce some important news.

The centralization of information and the resulting separation in SENSE–PLAN–ACT phases represent the major benefits of the WPS and determine its importance in the described architecture. Data on the perceived world are centralized, and they are described in a common reference system, thus not needing any particular knowledge on the sensor characteristics.

C. Modularity

The whole architecture is realized to achieve the largest possible modularity, which is obtained by exploiting hierarchical planning principles, as shown in Section VIII-A. In the same way, perception applications are divided into modules, each one having a definite goal. At runtime, the system is able to check which applications are available, and consequently, it can define the perception level the vehicle can achieve; this task is the main purpose of the Mission Manager. An ad hoc communication layer, which is called the VisLab bus (VLBUS), connects the architecture and allows for information exchange between the system components.

The VLBUS exchanges information between apps and threads on the same machine (and on different machines as well) in a completely transparent and efficient manner: in this way, all the components of the system are realized as separated units. The VLBUS is an abstraction that models interprocess communication as a data bus; several data buses can coexist, each of them with many independent virtual lines. Each line represents the topic of the flow of data.

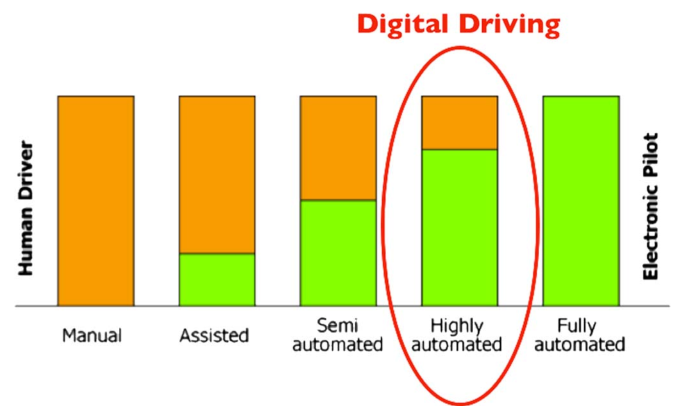


Fig. 16. Automation levels: Assisted (only human control), semiautomated (automated intervention is limited to a few seconds), highly automated (the system is in control of the vehicle for a long time), and fully automated (the system is in control of the vehicle for the whole time).

D. Vehicle–Driver Cooperation

A highly automated driving paradigm, called Digital Driving, will be developed and added to the system. This new architecture aims at handling the cooperation between driver and vehicle. The basics of Digital Driving are

- presence of the driver;
- grouping of all the ADAS under the same HMI;
- use of the human driver as ground truth.

With "Digital Driving," we define the capability of driving a vehicle using only high-level commands without direct interaction with the vehicle actuators. This type of driving, as shown in Fig. 16, is one step below the fully autonomous level, and it uses all the features of an autonomous car to ease the driver's task. The architecture also needs to handle any vehicle–driver conflict that can arise either during a digital driving session or a totally automatic session. The interaction between the two actors (driver and vehicle) is bidirectional, i.e., the driver may require the vehicle to perform a given task, but at the same time, the autonomous vehicle can query the driver as a source of knowledge and as ground truth.

IX. Conclusion

This paper has presented VisLab's approach to future autonomous cars, including considerations on hardware and software. The main driving forces being low cost and deep integration, VisLab is currently focusing on vision technologies to implement the perception layer. Indeed, other sensors demonstrated the ability to deliver a very robust set of data about the surrounding environment, but their cost and installation requirements may not favor their integration in future series vehicles. To test and challenge those design choices in a variety of real situations, a very extensive and unique test has been organized. To run, the test special vehicles have been equipped with subsystems of the developed technology, which is currently integrated on BRAiVE: VisLab's most advanced prototype.

Not only was the data acquired during this test used to assess the system performance, but it helped improving the current system and developing new functions as well. Apart from this very extended data set, which will soon be shared with the intelligent vehicle's community, one of the most important results is the awareness that vision technologies offer a great potential to overcome the limits of current technology (high cost and invasive installations) and can be therefore considered a valid and viable alternative, although it still requires further research.

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