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A 13,000 km Intercontinental Trip with Driverless Vehicles: The VIAC Experiment

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I. Introduction

Issues like the improvement of safety conditions, the optimization of transport network usage, energy consumption reduction or pollution decrease have been given a large emphasis in the last years. The full or partial automation of different driving tasks is then seen as a potential solution for these problems and the interest towards research and applications for Automatic Vehicle Driving is now flourishing [1]–[11].

VisLab has a many years experience in developing Advanced Driver Assistance Systems [5], [12]–[14], and prototype vehicles including ARGO [15], TerraMax [5], [16], [17], and BRAiVE [18], [19], the

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***Abstract*—In recent years the interest in autonomous vehicles has incrementally increased. After the DARPA Challenges new fields of application as agricultural, construction, mining, and also nautical are continuously opening up. In this paper a huge test is presented, the first of this kind in the history of vehicular robotics. A trip from Italy to China with four electric autonomous vehicles will be described focusing on all aspects of the challenge, from the managing issues to the most technical ones. A vehicle-following application (or *virtual towing*) is the system under test for a three consecutive months and 13,000 km long unique experience.

latter being VisLab's latest prototype now integrating all the systems developed by VisLab so far.

Thoroughly tested both on and off-campus in Parma and other cities, BRAiVE performance has been satisfactory but in very well structured scenarios and predictable environmental conditions. Further tests in the same conditions would have brought limited advantages since the main factor to be tested is the system's ability to cope with a plethora of different scenarios. The next test would then have to be extensive, heterogeneous, and involve driving in real traffic conditions. This idea led to VIAC, the "VisLab Intercontinental Autonomous Challenge," a 13,000 km long automotive driving test, a unique scientific and human experience and so far the most ambitious and complex endeavor of VisLab's history (see complete route in Fig. 1). The main target of this extensive test is twofold; to test already developed systems in order to improve them and to collect a large amount of data for in-lab processing.

Section 2 of this paper briefly describes the organizational issues of the trip and some of the most pertinent events. Section 3 illustrates the requirements and peculiarities of VIAC vision-based intelligent vehicles. Section 4 outlines the experiment preliminary conclusions, while Section 5 ends the paper outlining our perspectives in the evolution of intelligent vehicles.

II. Challenge Accounts

Non-polluting transportation systems are increasingly employed technologies (e.g., Citymobil [20] and Dustbot [21], the Venturi challenges [22] and the zero-race [23]); for VIAC four Piaggio Porter electric power vehicles were selected: the extra burden of frequent stops for traction battery recharging (2 h and about 100 km autonomy for each run, 8 h full recharging) was compensated by the ease of the x-by-wire development added to the vehicles.

The project involved for over a year about 30 people among researchers, post-doc, Ph.D. candidates, Master and Bachelor students. Different teams were created to cope with the many aspects of the project that had to be managed (i.e., sensing, planning, vehicle control, hardware setup, communication, tests and demos planning) but, regardless the specific team affiliation, every individual working at the project was also assigned to logistic duties before and during the trip. The vehicle's limited range posed additional logistic problems even during the development and test phases: each test had to be carefully planned since after about 100 km the vehicle had to be recharged for 8 h allowing a maximum of two runs per day per vehicle.

The whole VIAC convoy was made of eleven vehicles: four autonomous electric power vans, two trucks for spare parts storage and mechanic shop, a car transporter carrying an electric power generator for the autonomous vans traction batteries recharge, four RV's for team accommodation [see Fig. 4(i)]. People were organized in overlapping shifts to pass over information and duties.

A vehicle-follower approach (*virtual towing*) had been chosen to deal with the lack of maps for a large percentage of the route and to face the very different conditions of

FIG 1 The route covered by VIAC: more than 13,000 km covered travelling from Italy to China.

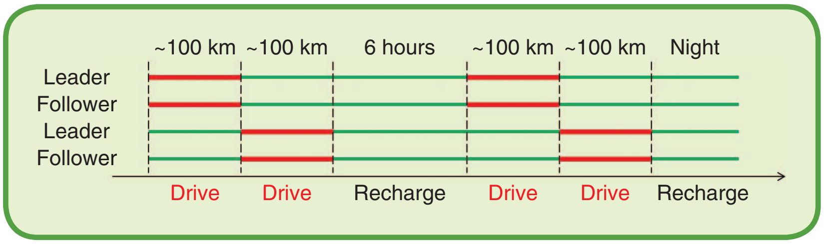

FIG 2 Drive/Recharge pattern of both Leader-Follower couples: while the first couple are driving the others are transported on the trucks; after about 100 km (a little less than 2 hours driving) the couples are swapped. After two drives—about 200 km—the four vehicles are connected to the generator to complete the recharge of all batteries, then another two drives follow until a longer break for the night.

road, weather, infrastructures, temperature, traffic, and unpredictable behavior of other road participants that the vehicles would have encountered during the trip.

Two electric vans were driven together but with different behaviors; the first one tracing the route for the second to follow, driverless. Once the traction batteries went flat, both vehicles were swapped with the two charged ones performing every day from two to four autonomous runs, as in Fig. 2 pattern.

FIG 3 Example of swapping operations on a country road near a main state road in Russia.

Early in the morning two vehicles were prepared for the first autonomous run of the day while the other two were loaded on the trucks. After about two hours, when the batteries went flat, the convoy stopped to swap the vehicles. The second couple were downloaded from the trucks using the car transporter as a ramp, then the first couple was put on the transporter starting its battery recharging during the second autonomous run (the power generator allowed vehicle batteries charge while the convoy was driving). At the end of this run the convoy stopped and waited about six hours to complete the batteries recharge, leaving again around mid afternoon. After that, another autonomous run was performed while the second couple completed the

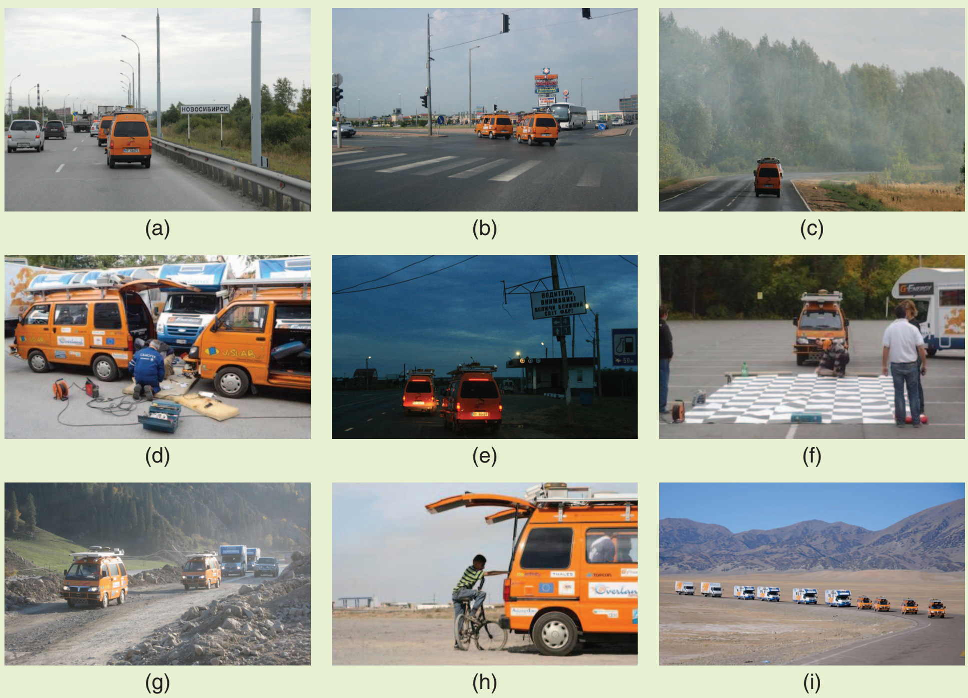

FIG 4 Images from the journey: (a) vehicles entering the city of Novosibirsk in Siberia, (b) turning manoeuvre in Russia, (c) travelling in the outskirts of the 2010 summer wildfires in Russia, (d) repairing session of the vehicles, (e) travelling by night in Russia, (f) calibration of the vehicles sensing system, (g) off-road track on the border region between Kazakhstan and the Xinjiang Uyghur Autonomous Region of Western China, (h) a Kazak child looks at the vehicles processing equipment, and (i) the complete Viac convoy going across the Tien Shan Mountain chain.

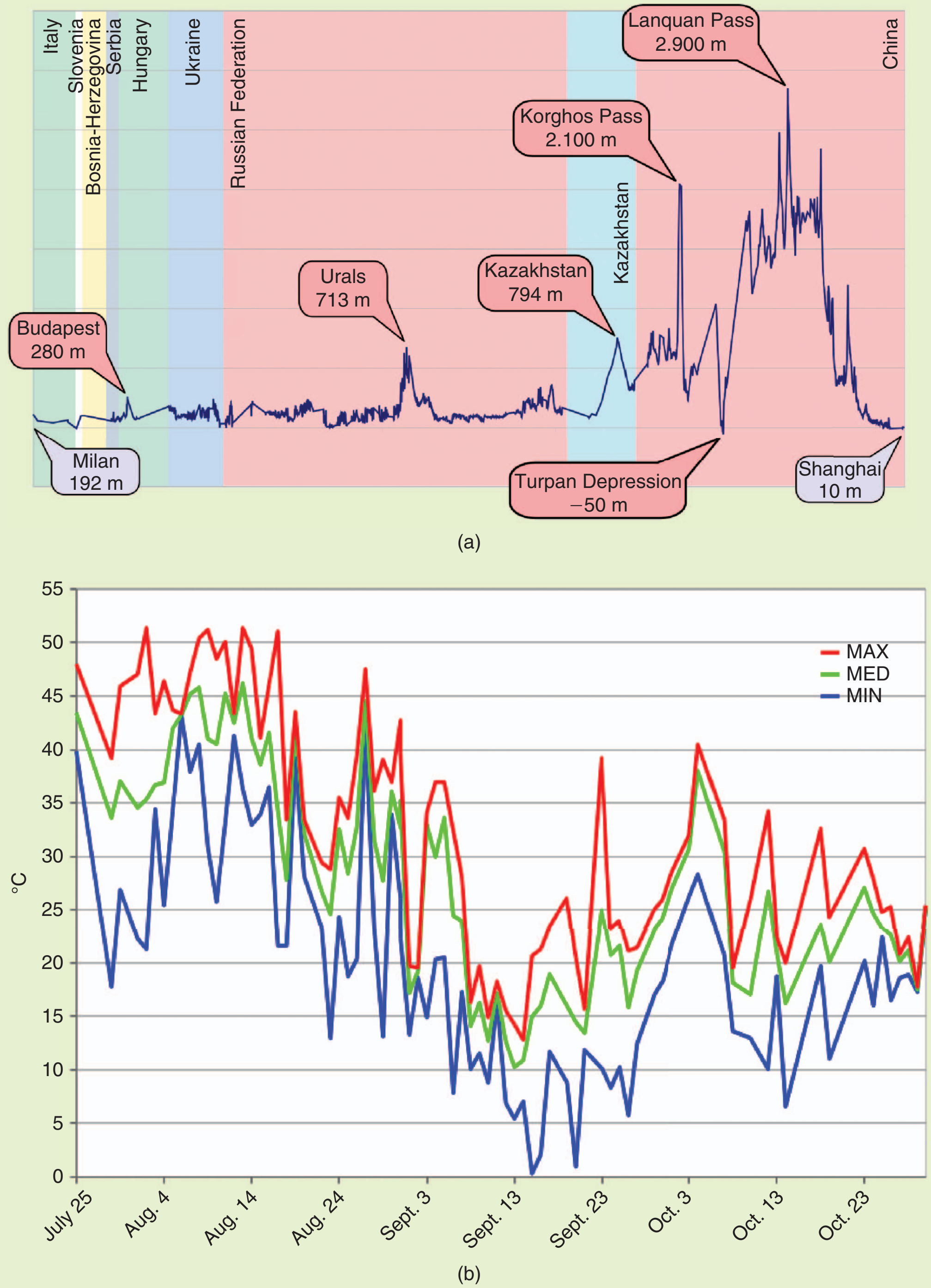

FIG 5 (a) Elevation map showing the most significant altitudes reached during VIAC and (b) temperatures recorded by the GPS-INS unit on the vehicles rooftops.

batteries charging, then the vehicles were swapped and the last run started. Late in the evening the convoy stopped and the whole night were used to allow the charge equalization for all vehicles batteries (over 10 h).

Swapping the vehicles has been a quite complex operation as involving all the autonomous vans and the car transporter it required large spaces to be safely performed (Fig. 3). For this reason the vehicles had to be swapped either in rest areas along highways or in any other clearing along state roads as soon as available, even if the batteries were not completely discharged.

These requirements made the swapping operation one of the most critical issues during the trip as they limited the automated runs length even in favorable road and weather conditions. But the biggest problem of all has been the weak traction batteries performance that, maybe due to intense use, allowed as maximum distance covered in a day about 250 km (see Fig. 7) instead of the nominal value of 400 km (see Fig. 2).

During the trip the vehicles, equipped with the same sensor suite and identical control software, have been tested in all possible configurations (swapping couples and different couple's leader with follower) to collect a complete set of data. This task was accomplished by the leading vehicle recording the data coming from all its sensors (more details about data recording are illustrated in Section III-A). The data collected covers a number of different scenarios, from busy urban roads in many great Eastern Europe cities like Belgrade, Budapest, Kiev, and Moscow to highways in the Siberian tundra, from the winding rural trails across the great Tien Shan Mountains to Shanghai's downtown traffic.

Fig. 5 gives an idea about the variety of scenarios encountered by the convoy during the trip in terms of elevation and climate conditions. The heat found in Eastern Europe and near Moscow due to an extraordinarily hot summer caused to the vision systems some hardware overheating problems whereas the cold temperatures across the Ural Mountains heavily pulled down the traction batteries duration as did climbing the mountain pass between Kazakhstan and the Xinjiang Uyghur Autonomous Region of Western China where the steep slope brought down the length of each run. A part from a few rural roads and the big stretch from Kazakhstan to China where huge roadworks were being carried out, the most challenging scenarios have been urban areas (see Fig. 6). Weakness of the GPS signal, frequent slowing downs followed by sudden accelerations and different driving habits of the local drivers made the autonomous driving task very difficult to be safely achieved so that in particular situations even the follower needed to be driven manually. For example, in case of traffic jams where continuous breaking and accelerations occurred, the brake actuator often overheated becoming unreliable. In addition, in some eastern cities, like Moscow, the lanes were severely occluded by other drivers putting the autonomous vehicles in dangerous situations when they were not observable.

Fig. 7 shows how many kilometers were driven per day by every van. Due to some documentation issues for the autonomous vehicles at the beginning of the trip and along the route (e.g., border and traffic police controls), some days no autonomous runs could be driven in order to get to Shanghai's Expo on the 28th October, as scheduled. The overall distance autonomously covered by the vans has been computed in about 8.300 km [24].

III. Autonomous Electric Vehicles

The design and sensors selection for autonomous vehicles are generally driven by the knowledge on scenarios to be faced. Nevertheless, in the VIAC case, no expectations on scenarios and assumptions on other vehicles behaviors could be made. Therefore, the sensing technology installed on the vehicles stemmed directly from the findings and experience gained using BRAiVE [18], [19], the main differences being the need of cross-country driving skills and the sensors integration in the cars chassis.

For VIAC, every device had to be kept handy for maintenance operations, therefore all sensors and PC's were placed in reachable positions. Making all the hardware equipment well visible (see Fig. 8) showed clearly the prototype nature of the vehicles, a very useful feature when the vans were presented to the press, authorities and public, who could easily understand at a glance that they were looking at a scientific experiment. To be able to use any vehicle in any autonomous driving configuration possible (i.e., leader, follower, standalone) and to readily swap it with another one in case of failure, the 4 electric van setups were identical, with the same hardware equipment and sensors placement. On the other way this choice meant putting additional equipment time (each vehicle must support all possible usage patterns).

(a) (b) (c)

FIG 6 Critical situations: (a) driving along a gravel road in Russia, (b) on the route from Kazakhstan to China, unpaved because of roadworks, and (c) entering Shanghai on Nanpu Bridge with a car cutting across from the right between the two autonomous vehicles.

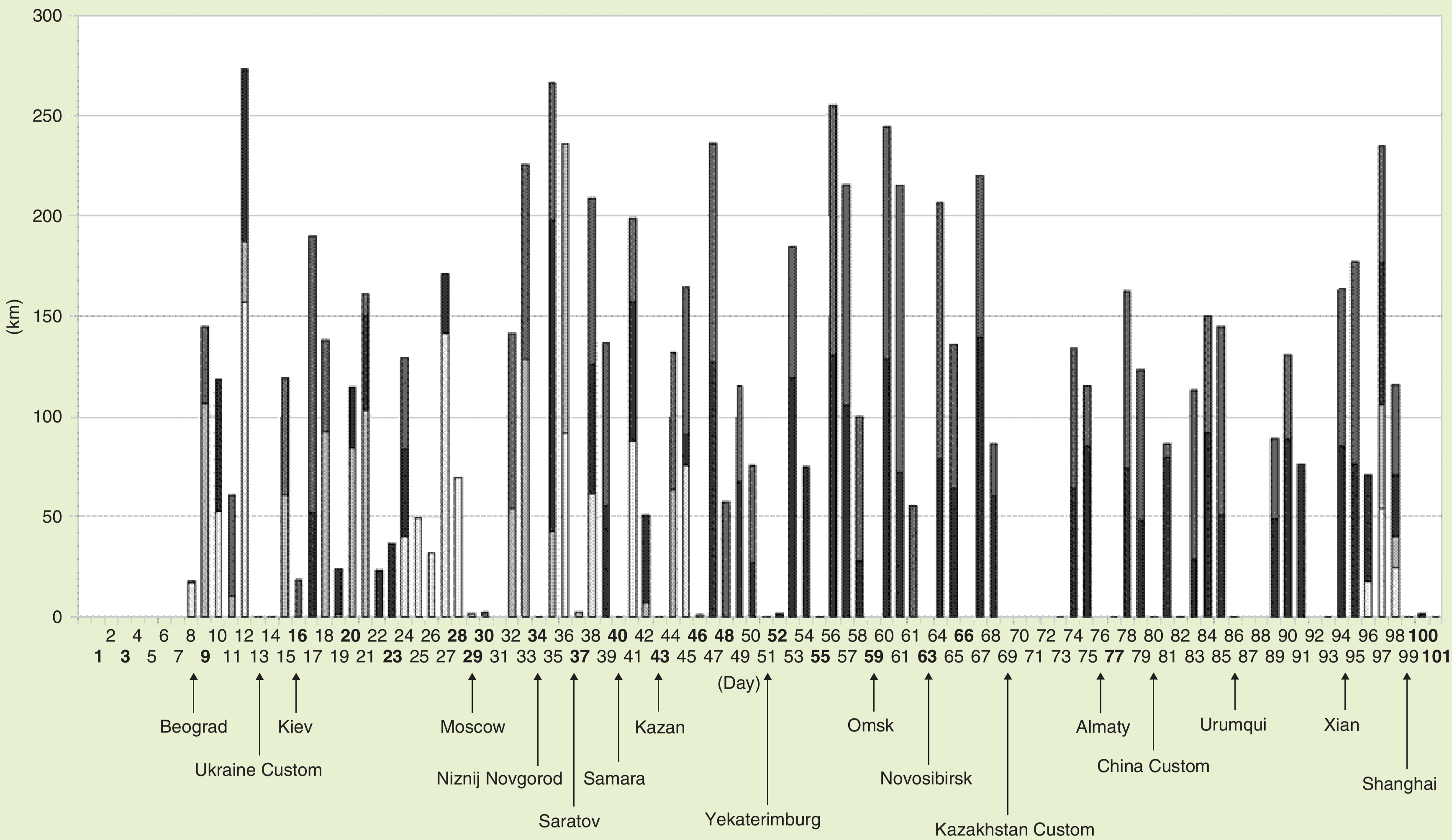

FIG 7 Each column shows how many kilometers were driven each day by each autonomous vehicle, denoted with a different grey tone column section. On the x-axis the travelling days numbers are reported, in bold fonts to indicate when demos were held. Having incurred in delays along the route (e.g., police controls, long waiting hours at the borders) some days no autonomous runs could be done.

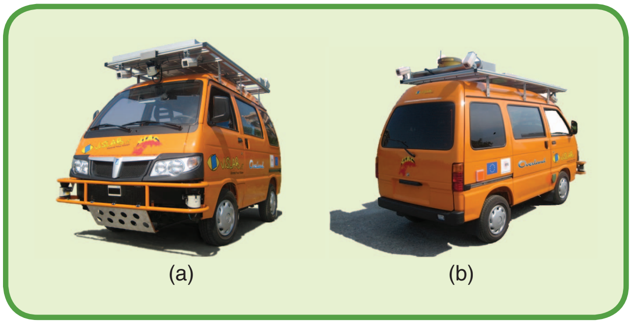

FIG 8 (a) Front and (b) back views of a completely equipped VIAC vehicle.

For the sensing systems, those to be tested during VIAC were a subset of the ones available on BRAiVE. The possibility to record all data coming from the sensors would have allowed to test off-line other systems after the end of the trip.

A. Sensing Equipment and Capabilities

During the sensors choice phase, particular emphasis has been given to cameras since vision technology provides a more cost-effective way of sensing the environment with respect to laser scanners. Moreover cameras have many possible installation positions within the vehicle, while laser scanners used for mid-long term sensing need to be placed in front of the vehicle in the most prominent positions where cars are most likely to get hit by rocks, debris and other objects. To minimize this problem on the VIAC vehicles, the lower laser scanners were placed behind a frontal protective bullbar [see Fig. 8(a)].

Different sensing systems were developed to guarantee the widest monitored area around each vehicle (see Fig. 9). The final sensing equipment is made of seven cameras (five looking forward and two backward), three mono beam laser scanners and a four-plane laser scanner [Fig. 8(a) and (b)].

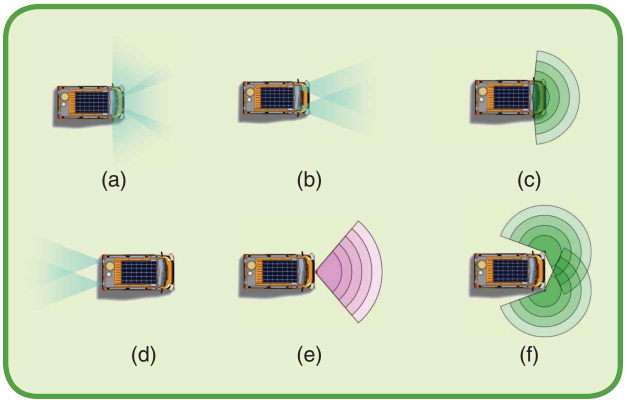

FIG 9 VIAC autonomous vehicles sensing systems: (a) *Panoramic Vision* cameras, (b) *Frontal Vision* cameras, (c) *Off-Road Sensing* laser scanners, (d) *Rear Vision* cameras, (e) *Central Sensing* laser scanner, and (f) *Lateral Sensing* laser scanners.

In the following a list of the sensing systems developed with their respective capabilities is detailed.

- *Panoramic Vision*: three AVT Guppy Firewire color cameras of 752 × 480 resolution for a 1/3" sensor with 3.5 mm optics and a 65° FOV each are synchronized and their images stitched together to obtain a high resolution approximately 180° frontal view for detecting and tracking the leader vehicle even when approaching a tight curve or a steep hill [Fig. 9(a)].
- *Frontal Vision*: two AVT Guppy Firewire color cameras of 752 × 480 resolution for a 1/3" sensor with 4 mm optics, 60° FOV and about 80 cm baseline form the frontal stereo camera system used for medium to short range sensing, to determine the terrain slope and detect obstacles and lane markings [Fig. 9(b)] thanks to the use of a Disparity Space Image approach [25].
- *Off-Road Sensing*: a mono beam Sick LMS-151 laser scanner with 270° FOV and about 30 m perception range is pitched down to monitor the ground in front of the vehicle; it provides information about the presence of ditches, bumps and obstacles right in front of the vehicle, specifically for (but not limited to) off-road driving [Fig. 9(c)].
- *Lateral Sensing*: two mono beam laser scanners, the same as that employed for off-road sensing, mounted on the corners of the frontal bumper are employed to detect obstacles, pedestrians and vehicles in the vehicle's immediate surroundings; each laser scanner has an aperture of about 270° while the depth perception is of about 30 m [Fig. 9(d)].
- *Central Sensing*: a four parallel layers Ibeo Lux laser scanner with 100° FOV and about 80 m perception range is placed in the lower central area to monitor the front of the vehicle; its four planes allow to partially overcome the usual problem of laser scanners: when the vehicle is pitching up or down, the laser beam points to the sky or hits the ground, making data acquisition worthless. With an aperture of about 100° and a depth perception of about 80 m, it is used to detect vehicles, obstacles in front of the vehicle. More precisely, its output was used to detect areas of attention to be further investigated using images acquired by the panoramic vision device [Fig. 9(e)].
- *Rear Vision*: the same stereo system as the frontal one, mounted on the back of the vehicle to perform short range obstacle detection [Fig. 9(f)].
- *GPS and Communication*: a Topcon AGI-3 GPS-INS unit on the rooftop provides positioning, inertial and temperature information. Moreover, this device is equipped with a radio communication system that can be used to broadcast in a short range (few kilometers) the data acquired. This would allow the leader vehicle to transmit a list of waypoints to the follower and therefore

enabling the follower to follow the leader even when the distance between the two vehicles does not allow visual or laser-scanner detection of leader vehicle. Due to strict radio broadcasting regulations of the different countries and due to the fact that the radio communication of GPS points was often unreliable, this has generally been used for demonstrations only.

B. Perception Algorithms and Capabilities

The sensors layout described in the previous Section provides extended sensing capabilities. Some of the algorithm that exploit these potentials have been directly taken from VisLab's BRAiVE experience, such as lane detection and stereo obstacle detection. Other algorithms were developed specifically for the VIAC expedition, to meet the very peculiar requirements of such an ambitious challenge.

The main sensing algorithms running on the vehicles are:

- **Lane Keeping:** lane detection is a basic, yet fundamental component of autonomous navigation; our algorithm uses just one camera of the frontal vision system and it is able to discriminate between solid and dashed markings.

Table 1. Each PC specifications, connections and duties on both leader and follower vehicle.

Processing and Sensors	Duties
PC 1 • Core2 Duo Mobile @ 2.10 GHz • 3-MB cache • 2-GB SODDR3 RAM connected to: • Touch screen inside the cabin • Local network	Leader Vehicle: • Mainly exchanges data and receives the processing results from PC 2 and PC 3 • Manages GPS and INS data • Records metadata indicating the different environments and weather conditions • Records linear speed coming from the odometer • Records angular accelerations (yaw, pitch and roll rates) from the inertial sensors • Records GPS position and time data Follower Vehicle: • Runs the path planner and the x-by-wire control • Mainly exchanges data and receives the processing results from PC 2 and PC 3 • Manages GPS and INS data
PC 2 • Core2 Quad Mobile @ 2.26 GHz • 12-MB cache • 2-GB SODDR3 RAM connected to: • 3 panoramic vision cameras • 1 Central Sensing laser scanner • 2 Lateral Sensing laser scanners • Local network	Leader Vehicle: • Records data from the panoramic vision cameras • Records data from the central sensing and the lateral sensing laser scanners • Dumps MEF • Feeds the path planner Follower Vehicle: • Acquires data from the panoramic vision cameras • Acquires data from the central sensing and the lateral sensing laser scanners • Runs the vehicle follower and the obstacle detector laser based functionalities • Runs the lane keeping, the obstacle detector vision based, and the driveable area localization algorithms • Dumps MEF • Feeds the path planner
PC 3 • Core2 Quad Mobile @ 2.26 GHz • 12-MB cache • 2-GB SODDR3 RAM connected to: • 2 frontal vision cameras • 2 rear vision cameras • 1 off-road sensing laser scanner • Local network	Leader Vehicle: • Records data from the frontal vision and the rear vision cameras • Records data from the off-road sensing laser scanner • Dumps MEF • Communicates with path planner Follower Vehicle: • Acquires data from the frontal vision and the rear vision cameras • Acquires data from the off-road sensing laser scanner • Runs the lane keeping, the obstacle ddetector vision based, and the ditch keeping algorithms • Dumps MEF • Feeds the Path Planner
FitPC • 500-MHz AMD Geode LX800 • 512-MB RAM connected to: • PC 1 second Ethernet port • Inmarsat BGAN satellite terminal • Webcam	Leader Vehicle: • Sends back to VisLab headquarters in Italy a low-resolution video stream and the GPS positioning data during the runs

Table 2. Example of disk occupancy for a sequence recorded during a 2 h run. The sum of data in the first column is about 7% of the total 1.5 TB of disk space available on each PC internal HDD. Includes MEF's 176.30 MB (0.16% Of the total sequence occupancy). 100% not reached because of approximations.

Sensor	MB	Sequence%
	Panoramic Vision	
Left Camera	18032.46	16.08
Central Camera	16682.62	14.87
Right Camera	16388.68	14.61
	Frontal Vision	
Front-Left Camera	20706.70	18.46
Front-Right Camera	20000.13	17.83
	Off-Road Sensing	
Ditch Laser Scanner	5395.14	4.81
	Lateral Sensing	
Front-Left Laser Scanner	6140.31	5.47
Front-Right Laser Scanner	6151.02	5.48
	Central Sensing	
Central (4 layers) Laser Scanner	2483.65	2.21
TOT	112157.01	99.98

- **Vision-Based Obstacle Detection:** based on stereo SGM disparity engine, it provides dense depth maps, in real time, and a reliable obstacle detection, taking into account also the physical characteristics of the ego-vehicle.
- **Laser-Based Obstacle Detection:** putting together data coming from single and multi beam laser scanners, this algorithm is able to perform a robust obstacle detection and terrain removal.
- **Vehicle Follower:** when running in Leader Follower mode, the following vehicle needs to detect the position of the leader vehicle; this is made coupling laser scanner processing, for candidate selection, and vision processing, for candidate validation and leader identification.
- **Driveable Area Localization:** a dedicated laser scanner is used to detect ditch, berms and curbs for off road navigation.
- **Path Planner:** the output of the previous algorithms is used to compute the best path and consequently how to act on the x-by-wire system. This task also includes emergency actions like full-stop braking, i.e., to avoid obstacles.

C. Processing Equipment and Capabilities

On each vehicle three off-the-shelf PCs are connected by GbE and placed in the trunk.

All the PC's and laser scanners are connected to a 1 Gbps hub.

Each PC can be accessed and controlled using a VNC connection from a laptop plugged into the hub.

A USB to CAN interface connected to PC1 acts as a bridge to the x-by-wire system, allowing vehicle control and its status reading. Another USB to serial interface is used to connect this PC to the GPS-INS unit which supplies positioning and inertial data, as well as half duplex communication between the vehicles driving, leader and follower. GPS and INS data are also broadcasted on the local network to be used by the functionalities running on the vehicles.

Basically the PCs inside the leader vehicle were mostly used to dump the data for in-lab post processing and checks, while the PCs inside the follower van had different processing and control tasks. In both cases they dumped the *Master Event File* (MEF) a ASCII format file that, for each line, encodes data like CAN messages, GPS output, inertial sensors output, timestamp, and system engage/disengage on the follower vehicle. Table 1 gives a detailed overview of both the leader and follower vehicles PCs and their duties.

The large amount of data to be stored (up to a few hundred GB for each run—see Table 2) required frequent backup operations from each PC's internal 1.5 TB HDD to other external 1 TB USB HDDs. A very time-consuming operation that implied many problems concerning its scheduling: the backup was done almost every day (depending on the amount of data collected), and usually in the evening, when the convoy had to stop for the night, or during the demo events in the cities visited.

Moreover, if backups could not be performed on a regular basis, the amount of data to be stored quickly grew up requiring lots of electric power from the power generator for the PC's to transfer all the data (the transfer rate of USB 2.0 devices being the most problematic bottleneck) so that none would have been left to charge the vehicles batteries. When this situation occurred, the operations had to be suddenly suspended.

At each shift of the VisLab crew the HDDs already full were handed over to the people who were leaving the expedition while some other ones, previously emptied back at VisLab facilities in Parma, were taken to the expedition by the incoming shift.

D. Human-Machine Interface

There are two different interfaces, the former was used by the follower vehicle to control the path planner and the latter was used on the leader vehicle to record environmental conditions.

Fig. 10 shows the HMI for the path planner: it allows to enable and disable autonomous driving and other functionalities; moreover some information about the vehicle status and the path planner processing results are shown.

The buttons for the autonomous driving are placed on the top right corner of the interface. Close to these there are the control button for the driverless guidance functionalities. The leds above are used to indicate the presence of problems caused by malfunction in the hardware setup.

Below these controls is the bird's eye view of the environment with the detected obstacles and the trajectory to follow. Moreover the path planner interface shows information about the steer status, the acquired GPS data, the battery charge of the autonomous driving system and some computational results like speed, target set point and trajectory data.

Fig. 10 shows the interface used by the leader to manage the recording of different sensors data like camera images, lasers obstacles points, GPS and vehicle speed data. The interface allows to complement the recording set storing additional information about the vehicle's surrounding environment: weather, traffic, sun light (sunset, sunrise, day, night) and the route type (urban, rural, highway or off-road). Moreover the recorded sequences may be tagged using dust and frontal sun labels. The button "OTHERS" allows the user to create new labels for all unlisted situations.

E. Actuating Equipment and Capabilities

All the vehicles are equipped with a full x-by-wire system.

In a number of modern cars, brake, throttle, and steering can be controlled via CAN. Unfortunately, the vehicles

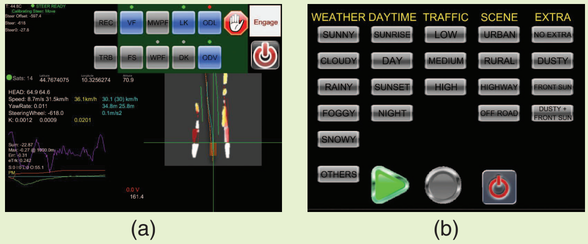

FIG 10 Human Machine Interface of the path planner (a) and of the leader vehicle (b).

that Piaggio & C. SpA gave to VisLab as sponsorship do not feature this capability and required the development of specific actuation devices controlled through a dedicated CAN bus. For safety purposes the actuating system can be manually overridden by any user at any time. It is possible to activate/deactivate the x-by-wire system with a button on a touch-screen display placed in the cabin. It is also possible to turn on/off this system by pushing either one of two double control switches placed in two different positions in the vehicle's cabin [Fig. 11(a) and (b)].

Furthermore, the CAN bus technology allows to efficiently manage the emergency stop commands: either when the button is installed on the vehicle or on a wireless remote system, the control works over the path planner and activates the brake to obtain the shortest braking distance, push the speed to zero and maintain the steering in a fixed position [see scheme in Fig. 11(c)].

To provide reliability of the actuating systems, the path planner manages all the different inputs coming from

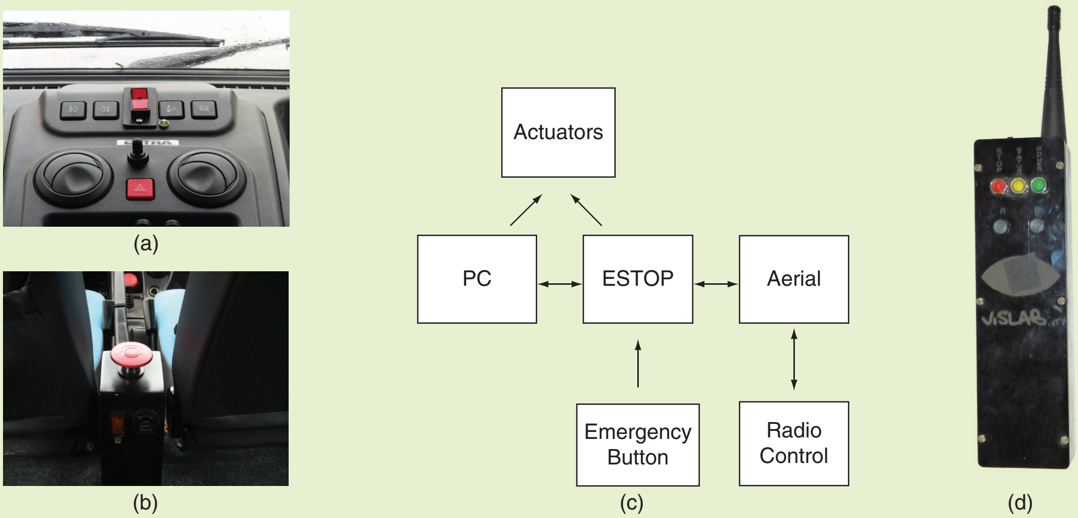

FIG 11 Switches of x-by-wire system: the 2 red switches are placed (a) in the front and (b) between the front seats, under the red emergency button: both must be switched on to give power to the system. (c) The E-stop architecture and (d) the emergency radio control.

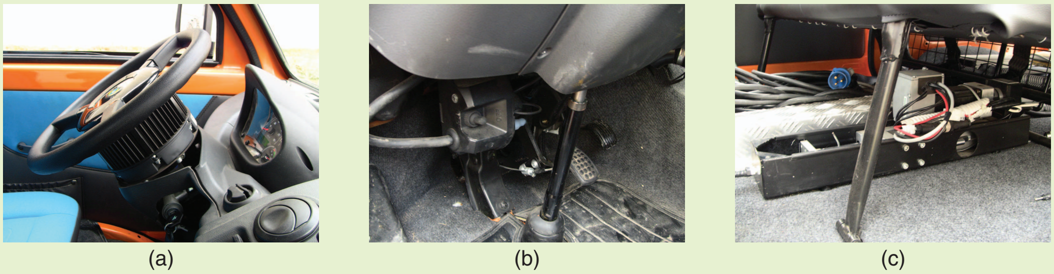

FIG 12 (a) Lateral view of the AES-25 installed under the steering wheel and linear actuator installed on-board of the vehicle: (b) detail of the brake pedal and (c) linear actuator.

cameras and lasers, the GPS-INS unit, and the high level control interfaces. The kinematic model is defined according to these information: it provides the feasible speed v and trajectory curvature k that define the set point the control aims to reach.

1) *Throttle:* Being the vehicles electric, speed is adjusted by changing the duty cycle of the PWM controlling the engine. The x-by-wire system receives the vehicle's speed data from the GPS-INS unit if there is a GPS signal, or otherwise from a customized odometer device. This odometer acquires the signal from the Hall-effect encoder placed on each electric van's traction motor, decodes the signal and sends the information via CAN bus to the x-by-wire system.

2) *Steering:* The selected Topcon Accurate Electric Steering-25 [see Fig. 12(a)] is an electronic steering wheel that can be controlled via CAN bus through a proprietary protocol. It is directly connected to the steering wheel column and controlled in position, speed, and torque through messages running on the CAN bus. Internally the set-point is followed using a PID controller.

3) *Brake:* The brake system has been implemented by an electric motor which acts directly on the brake pedal [Fig. 12(b)] using a linear actuator [Fig. 12(c)]. Since the electric vehicles are equipped with a mechanical brake, it would have been impossible to intervene at electronic or hydraulic level.

Moreover it is mandatory to allow the driver to override the system behavior when the system is either braking or not; therefore a linear actuator to directly control the brake pedal has been selected.

In particular when the system is braking it is necessary to disengage the automatic controller (with a specific button) in order to release the brake cable and allow the driver to manually operate. Vice-versa when the system is not braking the driver has the priority on the controller and could act directly on the brake pedal. An electric motor was placed under the back seats and connected to the brake pedal with a steel cable [see Fig. 12(b)]. The actuator can reach a 1500 N axial dynamic force at 200 mm/s and may be easily controlled via the CAN interface.

4) *Emergency systems:* The E-stop (Emergency stop) is a system to halt the autonomous vehicle when a dangerous situation occurs. It runs parallel to the autonomous system and is made with dedicated hardware for real time functioning and high reliability. The system is composed of an emergency button [Fig. 11(b)] installed inside the vehicle's cabin, a radio control [Fig. 11(d)], and an aerial [Fig. 13(c)] for communication between radio control and E-stop board. The radio control and aerial consist of a couple of radio modems (operation frequency 869 MHz, transmission power 500 mW, 20 km range with clear line of sight) that transmit status messages or stopping alerts. The status message is also used as a ping-pong message to check whether the vehicle is reachable via radio control. The E-stop board consists of a microcontroller (Microchip PIC18F258) with specific firmware to obtain a real time system and decrease fault probability. This board controls if the path planner is working well, exchanging specific messages through the serial bus. Not receiving these messages in a specific time interval, it sends a warning to the user via radio modem.

In case of an emergency situation there may be three different behaviors:

- if the path planner works fine then the E-stop board activates the emergency routine sending a message and everything is handled by the path planner
- if the path planner does not work correctly then the E-stop is directly connected to the actuators that control throttle, steering and brake. The actuator immediately pushes the brake, and the E-stop board cuts off power to all the actuators
- if there is not communication between path planner and E-stop but both systems work correctly, the E-stop board has the highest priority and the path planner commands are ignored by the actuators.

To further increase the autonomous vehicles safety, steering and brake control may always be overridden by direct human intervention.

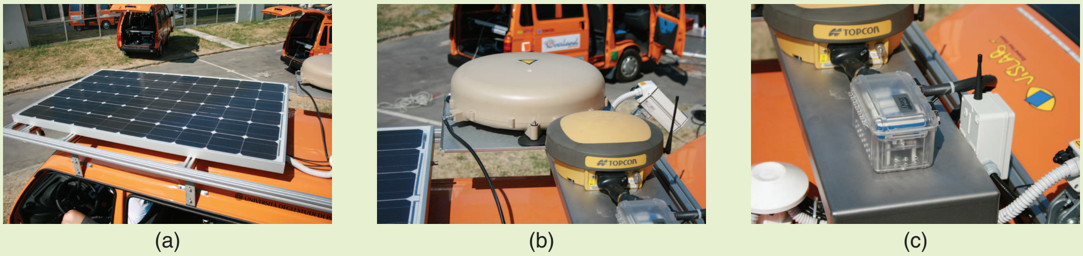

FIG 13 The complete set of additional devices on one of the vehicle's rooftop: (a) close-up of the solar panel, (b) satellite antenna and GPS-INS unit, (c) CO_2 sensors in their transparent placement box and the E-stop aerial grey box.

F. Other Devices

Completing the electric autonomous vehicles on-board set of sensors are other few devices.

1) *Solar panels:* Each vehicle mounts a single solar panel on its rooftop [see Fig. 13(a)]. Weighing 20,5 kg on a $1640 \times 992 \times 50$ mm surface, the panel is made of 60 high-efficiency 156 mm mono-crystalline silicon solar cells and produces a maximum power of 240 Watt which charges the whole vision system battery of 100 A/h in about 5 hours at maximum power (the vision system battery absorbs 100 A/h supplied by a 20 A/h charge regulator).

2) *Satellite equipment:* VIAC communication equipment included a land-vehicular rack-mountable terminal with a tracking antenna [see Fig. 13(b)] which provided high-speed data and voice communication via satellite through BGAN (Broadband Global Area Network). Once the tracking antenna has been positioned on the rooftop, the transceiver terminal inside the vehicle acts as a router to which any communicating device as a phone, computer or network switch may be plugged-in, letting the users be online.

While on the trip, at every vehicles swap the satellite equipment had to be shifted from one leading vehicle to the other and was used to send back to the laboratory in Parma the GPS data points necessary to trace live the route completed by the convoy, plus for other personal activities as connecting to the Internet and calling home.

During the whole VIAC expedition, also coordinate points were sent back to servers in Parma. The total satellite bandwidth usage was more than 13 GB (about 152 MB per day) and 482 minutes of voice traffic for both private and work calls. Sending back to VisLab laboratory in Parma the information collected during the trip live has been performed via an interprocess communication based on a network socket created by a server in listening mode for client connections. For each vehicle travelling on the expedition a client process was created to handle the data transmission: GPS and inertial sensor measurements were both sent to the server through the satellite equipment operating as a router. Each client transmitted through the satellite a data packet containing the sender's address, the vehicle information and the server's destination address; the satellite transferred the packet to the server encapsulating the data according to the network protocol specified by the client. According to the client's requirements, data may be transmitted by using either UDP or TCP protocols thus both a datagram and a stream socket have been implemented by the server. To guarantee secure data transmission the communication channel has been protected against denial of service attacks: the server filtered all incoming transmissions checking the data sender and the address specified in the packet. Sent data were updated every 3 m and close GPS points were discarded so to avoid an excessive number of points management workload. With such a solution, data traffic was limited to 1 KB every 10 m for a total of 7039 GPS points collected during the whole trip. All transmitted data were saved in a local database back to Parma and used to create an XML file containing each vehicle last position coordinates in terms of latitude, longitude and altitude values, its speed, the external environment temperature and the segments connecting the GPS points with their respective date. To view in real time the vehicles information, a live-tracking map made using Google Maps APIs was included in VIAC website Tracking section. Being the GPS points updated with low frequency, the route on the map, if zoomed in, does not appear as a smooth line but instead as the connection of many small segments. Besides, to avoid access overloading problems on the website during the trip progress, the XML file was updated periodically at the time—every 10 m—and then "frozen" once the trip had ended.

3) *CO_2 sensors:* In cooperation with IBM for the Green- haviour Project [26], a couple of CO_2 sensors and a smart-phone were placed respectively on the rooftop [see Fig. 13(c)] and inside the cabin of one of the vehicles (leader or follower indifferently) travelling during the trip. The carbon dioxide emissions data acquired by the sensors

were buffered on the smartphone memory and, as soon as a GSM network was available, sent via GPRS to IBM databases set in Europe. The information acquired were used to trace out a map of the CO_2 amounts along the trip.

IV. Preliminary Conclusions

Approximately 20 TB of data acquired in a large variety of scenarios have been collected during the expedition and are currently being uncompressed, synchronized and analyzed. At work ended, this enormous data set will be available for sharing with VisLab partners and academic institutions as research and benchmark material.

A huge database of this kind is of utter importance to develop and test vision algorithms. Getting and equipping a vehicle with a sensor suite to acquire synchronized data from all its sensors is not a trivial task, economically demanding and very time-consuming. To have access to such a varied database of synchronized data coming from different sensors is of enormous advantage for the whole research community and should move closer the day when the autonomous vehicle will get from the stage of prototype to that of a car for everyday use.

In order to thoroughly evaluate VIAC vision algorithms outcome on the acquired data, once a good amount of them will have been uncompressed and ready to use, VisLab secured 20,000 processing hours on the largest Italian supercomputer. Results of this experiment are still, at the time of this article, just qualitative. On highways or well structured and maintained roads where other road users behavior usually involves a reduced number of possible maneuvers, the vehicles were able to drive autonomously for the whole length of each run and at good speed (between 40 and 50 km/h, the expected speed for an electric vehicle driving with fully charged batteries).

In urban environments though, where road users behavior may be very unpredictable, where the GPS signal is often lost due to electromagnetic noise and where heavy traffic conditions are very likely to be found, the vehicles could drive autonomously for shorter time periods and at lower speeds, making the actuation process harder on the commands.

Around 13,000 km were travelled from Italy to China; due to bureaucratic and technical problems some days no autonomous runs could be driven to fulfill the timeline for arriving to the Expo. Anyway, the follower were able to cover around 8.300 km in autonomous mode. According to system logs it was necessary to switch off the autonomous driving in different situations up to about 20 km during the whole trip.

V. Perspectives

This unique test, certainly a great challenge for VisLab, also marked a milestone in vehicular robotics. The data collected throughout the trip will serve both to improve current perception systems and build new ones after further study and testing, essential to validate them for successful everyday use. Indeed the first market opportunities for such technologies will not be into an automotive environment in which many players are acting together independently. Applications like autonomous tractors or driverless vehicles in construction areas might be good candidates to start exploiting these innovations.

However, one of the most important lessons learned during this special event is that when driving in real traffic conditions, the autonomous vehicle not only has to follow some predefined rules, but also needs to understand when it is necessary to break them. In very congested urban areas during the trip there have been situations where observing the traffic rules would have put the autonomous vehicle in danger, being one of the few to follow them. For example right turning maneuvers with vehicles unlawfully overtaking on the right: a collision would have been very likely to occur; crossroads priority granting to vehicles coming on the right when other vehicles expected priority agreements of the sort "first come, first go": this could have led the autonomous vehicle (and those behind it) to a very long wait, potentially a deadlock; speed limits compliance with other vehicles driving at higher speeds than those allowed: overtaking maneuvers in such cases could have induced fast overcoming vehicles in the overtaking lane to brake abruptly.

So the next topics that urge to be investigated are the analysis of other road participants behaviors, the traffic flow pattern matching with the known rules, and the vehicle's behavior adaptation to a local 'interpretation' of such rules. Some very challenging tasks indeed, since they stem from the analysis of human behavior. But -after all- what should a robot do, if not helping humans in routine tasks and dangerous situations?

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