The BRAiVE Autonomous Ground Vehicle Platform ⋆

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Abstract: The interest in having an autonomous vehicle platform is driven by the long term objective, aimed by many research centers, of changing the transportation system world to move people in a safer and more efficient way. The BRAiVE vehicle presented in this paper is designed for this goal and with the idea of reaching it trough a series of steps, each one introducing more advanced systems and more complex levels of automation. A section describing the state of the art in this field introduces the paper showing the features of other similar projects around the world and pointing out BRAiVE's innovations. The paper focuses on the technical aspects involved in this project. Starting from the design choices, such as sensor placement, coverage or actuators performance, going trough development issues and solutions adopted to reach a high integration level for preserving the external look together with good ergonomics for the interiors. Conclusions collect the demonstrations in which effectiveness and the versatility of the vehicle has been shown.

Keywords: Automated guided vehicles, Autonomous vehicles, Image sensors, Inertial sensors, Obstacle detection, Detection systems

1. INTRODUCTION

The transportation systems world has seen many important changes from its origins. The historical trend observed is a gradual but continuous driving task automation from the simplest to the most complex. From the end of the 70's up to the end of the 90's spreading of systems like ABS and ESP triggered a lot of interest on Driving Assistant Systems. Today, while lane keeping and collision avoidance systems are becoming commercially available, interest on ADAS is being eclipsed by energy-related matters: manufacturers are now orienting their efforts to power vehicles with different sources in order to reach the zero emission goal with performance comparable with internal combustion engines one. However the research activity on autonomous vehicles has not been stopped. A big leap forward was reached with the DARPA challenges, as described in Braid et al. (2006), a significant investment by the main robotics research center to establish a new state of the art for autonomous driving. Getting a rich sensors suite and high-end processing capabilities is a difficult goal to match with a high integration level and the most advanced examples available today do not look like normal vehicles. The LUX vehicle, from Ibeo A.S., participated to the DARPA Urban Challenge 2007. The sensors suite counts 3 IBEO Lux, 1 Novatel GPS. Actuators have been added to gas, brake and steering control, while gear was already automatic. Even if it did not complete the qualifications, this car looks very clean and still is one of the best examples of how both 360° sensing constraints and integration should be matched. Outside the prototype looks like a normal car: the laser scanners have been integrated into the bumpers and the bumpers have been modified opening windows covered of plastic material transparent to the laser radiation. The GPS is put in a standard position over the roof in the back of the car together with a signaling light required by DARPA. Inside, an e-stop button has been installed in the center of the dashboard as requested by DARPA rules, while a power box is still visible is left visible in the trunk, together with a fan cooling. Al the other processing stuff is integrated under the trunk plane. The BOSS vehicle (Urmson et al. (2008); Ferguson et al. (2008)), build by the Tartan Racing team of Carnegie Mellon University, won the 2007 DARPA Urban Challenge. It is a 2007 Chevy Tahoe, 5.3LV8, 4L60 automatic transmission, 4wd, E-85 Fuel-capable. The X-by-wire system is based on a GM engine control plus electromechanical actuation. The sensing suite is impressive: 5 Continental ARS300 Long Range Radar, 8 SICK LMS-291 Short Range Lidar, one Velodyne HDL-64 Mid Range Lidar, 2 steered Continental ISF 172 plus 2 IBEO ALASCA XT Long Range Lidar and the Applanix mPOS-LV with dual antenna GPS and IMU for Pose Estimation. The computing system is 10 Intel Core 2 Duo blades @ 2.16 GHz in a compact PCI chassis and runs a Decentralized Software Architecture where multi-process systems are coordinated via a gigabit Ethernet communications layer. The motion planning evaluates over 1000 candidate trajectories per-second using the information from the multi-sensor fusion perception which generates moving and static obstacle models. BOSS is not exactly a model, from the integration point of view. Its huge amount of hardware cannot be easily hidden under the car body or inside the cabin.

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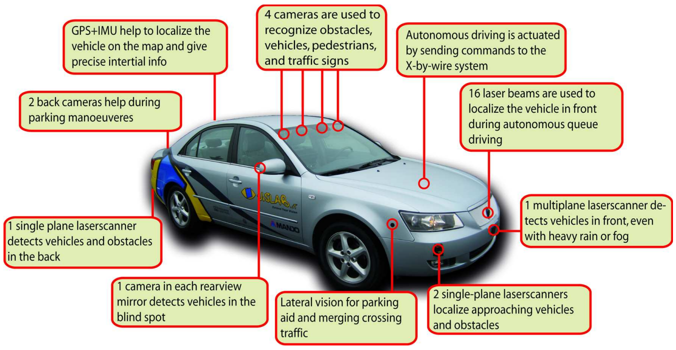

Fig. 1. Position and description on each sensor.

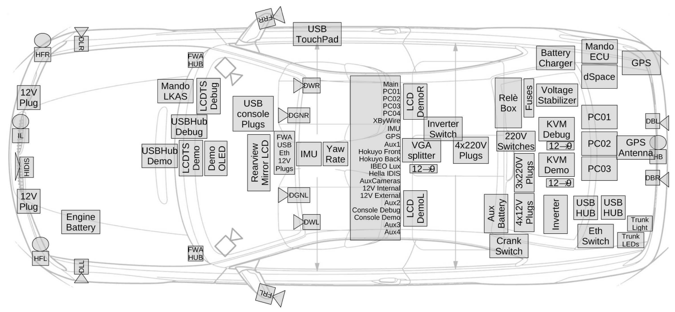

Fig. 2. The BRAiVE autonomous vehicle components location

This paper describes a new prototype of autonomous vehicle and system development platform. The novelty of this project is the high level of integration reached which makes this vehicle look like a normal car even if the sensing suite is superior to most vehicles having participated to the DARPA Urban Challenge.

BRAiVE stands for BRAin driVE, the idea being to enclose in a single name the double soul of this project: an artificial intelligence specifically applied to the autonomous driving task. BRAiVE has been developed around the concept of being a laboratory and a technology display. For this reasons even if the vehicle is features and sensors rich, both the external and internal look are designed to minimize the impact on observers, hiding as much as possible the technology filling the car under the surface. Fig. 1 shows the components mounted on BRAiVE and their location. Fig. 2 shows the location and type of each hardware component installed on this prototype.

The system components are divided in three main areas: sensing, processing and actuation. These areas are described in the following sections.

VisLab has a 15 years experience in treating in-road, off-road, marine and avionics vehicles. In 2000 with the project Argo, one of the first prototypes of autonomous vehicles, a tour of 2000 Km has been concluded driving 98% in autonomous mode. TerraMax, between the five vehicles that successfully concluded the 2005 DARPA Grand Challenge, was equipped with a custom VisLab vision system. In 2007 TerraMax2 running a more complex VisLab vision system, reached the finals together with other 11 top teams. Today, VisLab is involved in several projects as partner of the major world players in the automation field, vehicle makers, and system suppliers. In

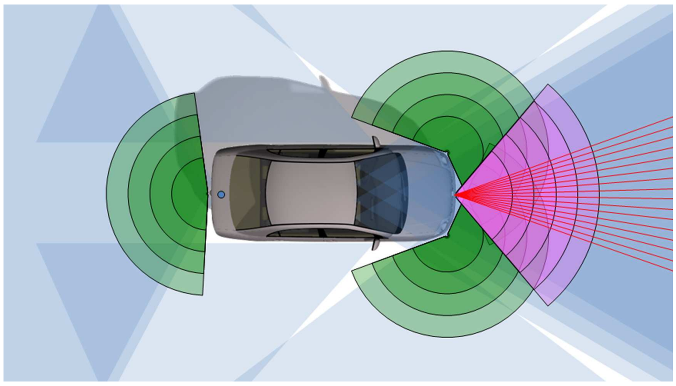

Fig. 3. Field of view covered by each sensor.

the next months, a great travel from Italy to China is going to be exploited by VisLab using all the technologies developed during its history.

The heavy modifications to brakes, steering and gas controllers made on BRAiVE, do not allow, under the current regulations, to matriculate it as a normal vehicle. However, the Italian law foresees circulation permissions for this kind of vehicles using appropriate license plates. Unfortunately this kind of license plate is not recognized in all countries. So in such cases the vehicle circulation is limited to private areas such as tracks and campus and outside these areas transportation must be arranged using other vehicles.

2. SENSORS

The BRAiVE sensing suite is based on 10 cameras, 5 laser scanners, 1 GPS+IMU, 1 e-Stop system. Sensors spread around the car to reach a 360° all around coverage are mainly concentrated in the frontal area, with 4 cameras and 4 lasers pointing in that direction. Sensors covering areas are depicted in Fig. 3. The vehicle has been designed as an ADAS development platform, using information accumulated by VisLab over a long experience on intelligent vehicles prototypes. The sensor suite is rich and redundant so that subsets of sensors may be employed to develop applications addressed to investigate the many topics by which the Intelligent Transportation Systems community is concerned (e.g. pedestrian detector, obstacle detector, vehicle followers, collision warning, traffic sign recongnition, parking slot detection, backup maneuver, collision detection, etc.). The developed algorithms may also be runned at the same time so to directly compare their results. Navigation and ego-motion information are also available as well as the access to all off-the-shelf data supplied via the car's CAN bus to complete the environmental perception necessary to drive the vehicle autonomously.

2.1 Cameras

Cameras mounted on BRAiVE are described in Tab. 1. Four DragonFly2 units, two color and two monochrome featuring two stereo systems with respectively short and long baselines, are placed behind the windshield whereas the others, all color, are placed one on each side of the hood and two at the back in the boot top. The FireFlyMV units, selected for their compactness, are placed inside the two rearview mirrors supports (see Fig. 5, top right). Both camera models, featuring a CCD progressive scan sensor, have been installed without their enclosures to ease integration in different locations. All cameras have the standard IEEE 1394 cable for power supply and data plus a cable bringing other signals available on the GPIO connector: additional power, trigger-in and strobe.

Table 1. Cameras specifications

Camera model	Resolution	Max frame rate
Point Grey DragonFly2	1036 x 776	30 fps
Point Grey FireFlyMV	752 x 480	60 fps

In order to obey space and weight constraints, low cost micro lenses have been mounted on all cameras. Their specifications are listed in Tab. 2.

Table 2. Optics specifications

Camera system	Focal lenght	HxV aperture
Stereo front (short baseline)	6.4 mm	73.76° x 58.86°
Stereo front (long baseline)	6.4 mm	73.76° x 58.86°
Lateral	4 mm	100.43° x 84.15°
Rear	4 mm	96.93° x 71.54°
Stereo back	2.2 mm	130.81° x 117.32°

The four front cameras have been maintained mechanically accessible so that several combination of optics may be tested depending on the application under development. Their layout also allows different camera configurations testing e.g. multiple stereo pairs with different baselines.

An additional set-up has been provided to easily add two other cameras looking respectively to driver and passenger. These cameras may be placed in the dash top part at the windshield base to perform driver monitoring tasks for smart airbags, alerts number reduction in case of assisted driving or special situations signaling such as driver's fatigue or sleepiness Zhang and shu Zhang (2006).

Each camera is tightly connected to the car chassis through a rigid orientable mount. that allows both resistance to vibrations and dumping that may occur during normal driving and camera orientation on each axle. Appropriate supports can be created to connect different cameras models available on the market to the mount allowing comparison between different sensors.

Cameras mounted behind a glass, under certain unfavorable lighting conditions, may generate images containing reflections and create recognition problems to the algorithms. These reflections are a well known problem for forward looking cameras that need to be protected against dust, rain and other flying objects such as rocks and insects in the motion direction. On BRAiVE this problem concerns only the four forward looking cameras and can be addressed with appropriate enclosures.

For the two side looking cameras this problem, togheter with waterproofing issues has been solved by putting an elastic membrane between the lens and the internal part of the car's external structure.

Rear looking cameras adopt waterproof lenses directly exposed to the environment while the two cameras on the trunk are covered with a metal part and the cut dividing the metal from the lenses has been filled with the insulator. Both the backward looking cameras employ waterproof lenses. The FireFlyMV cameras have been mounted on a board made waterproof using automotive sealing material thus keeping both mirrors still adjustable by the driver.

2.2 Lasers

BRAiVE's lasers specifications are listed in Tab. 3. Two UTM-30LX are mounted on the sides of the front bumper to achieve perception in the front and lateral area whereas a third one is placed on the center rear bumper to cover the back area (see Fig. 5, bottom right); mounting height is 40 cm. These devices have a single scanning plane which is oriented parallel in respect to the ground plane. A single echo is returned for each pulse. These sensors, designed for indoor robotics, offer acceptable performance also outdoor although their perception strongly depends on the amount of external light: in summer they can guarantee good detection up to 30 m. Even if not engineered for automotive use, these lasers have been selected thanks to their small size, low cost, and good price/performance ratio over similar products certified for automotive use. Sensors are fixed on a mounting similar to those used for the forward looking cameras since also in this case the angle between the car mounting plane and the sensor mounting plane on is 90°. Distance between mounting and car body has been finely adjusted in order to let the lasers appear from the front and rear bumpers.

Table 3. Lasers specifications

Laser model	Planes	FoV	Resolution	Range
Hokuyo UTM-30LX	1	270°	0.25°	$0.1 - 30\ m$
IBEO Lux	4	85°	$0.125 - 1°$	$0.3 - 80\ m$
Hella IDIS	1	16°	1°	$0.7 - 110\ m$

The Lux is placed in the front bumper's center. The car chassis has been modified to host the sensor's mounting cradle which allows to independently adjust and fix the laser's orientation on each axle. The mounting base principle is different from those of the front cameras: in this case the angle between the mounting plane and constraint plain on the car is 180°. The cradle also allows to adjust the mounting position along the forward moving direction since the final position of the laser must be aligned with the external part of the bumper.

Finally the IDIS laser is mounted over the Lux for obstacle detection in the forward looking direction (see Fig. 5, top left).

2.3 GPS and IMU

A Race Logic VBox II SX GPS logger is mounted in the trunk and connected to a compact GPS antenna mounted over the trunk. This GPS unit generates a 20 Hz signal available through the CAN bus, where 95% of absolute positioning samples fall in a 3m diameter circle. A Race Logic RLVBIMU02 Inertial Measurement Unit is mounted in the the central tunnel just over the the yaw rate sensor. This unit can measure linear accelerations on 3 axes in the range $\pm 1.7\ g$ with a resolution of 1 mg and an accuracy of $\pm 0.01\ g$; angular velocities are measured between $\pm 150\ °/s$ and with a resolution of $\pm 0.01\ °/s$. The yaw rate sensor has been replaced during the X-by-wire system installation, with a different unit having the same shape but a precision of 0.0626 $°/s$ and a rate of 10 Hz. All these three sensors are connected together with the Hella laser to a separate CAN-bus branch dedicated to sensors. GPS and IMU are designed to work independently, fusion between these two data can be performed by the processing unit when needed.

2.4 Other sensors

Being an off-the-shelf vehicle, BRAiVE also provides a set of information via CAN bus (see Tab. 4).

Table 4. Data via CAN bus

Data type	Frequency	Precision
Wheel speed	20 ms	0.125 km/h
Steering wheel angular speed	10 ms	0.1 deg/s
Vehicle speed	7 ms	0.125 km/h
Yaw rate	7 ms	0.0625 deg/s
Lateral and longitudinal acceleration	7 ms	0.01 G

3. PROCESSING

3.1 PCs

Three MiniITX computers are placed in the trunk. The motherboards are based on an Intel Core 2 Duo, with 2GB of RAM, 2 Ethernet ports, 2 firewire ports. In this way each one of them can be connected to a different set of sensors or CAN buses. Each PC is running a Fedora 12 properly customized to reduce resource consumption. The OS is installed on a compact flash card mounted on the motherboards solder side. 2 MiniPCI expansion slots are available to mount CAN boards, analog video boards or additional firewire boards. The power for each PC is stabilized using an automotive power supplier. This component can cope with current spikes coming from the engine ignition. As every other device on this prototype each PC has its own power key in the switch-box between the two front seats. Each PC has its Keyboard, Video and DVI Monitor (KVM) plugs connected to one of the four input of the Debug KVM switch and the VGA output connected to the input of the Demo KVM switch. This allow to see and control two separate outputs (demo and debug) from different PC.

3.2 DSP

All sensors are connected to data wires that go from the sensor's position to the trunk. Additional power plugs are also available to supply current to additional processing devices. Our work-flow is based on the following idea: when an application developed in a PC environment is mature enough, it is ported on a DSP platform for the final integration. BRAiVE has been designed with the necessary connections to support this integration process: almost any kind of DSP board can be attached in the trunk, connected to the appropriate sensors, and, if needed, to the CAN bus and/or to the speakers for driver warning purposes.

4. ACTUATION

4.1 X-By-Wire

The X-By-Wire system has been installed on BRAiVE in two days from Mando engineers and then modified by VisLab to improve integration and usability. 2nd generation Automatic Cruise Control (ACC), Electronic Stability Program (ESP) and Electric Power Steering (EPS) actuators have replaced the original ones. These new components can be fully controlled using CAN messages. When the XBW system is off, BRAiVE behaves, from the control point of view, 100% as a normal car. When the XBW system is on, appropriate CAN messages can be sent to enable the autonomous mode for each actuator separately. In this way it is possible to partially or fully automate the driving functionality. The fully autonomous driving capabilities are developed and tested in the campus area or using other secondary roads in agreement with the municipality. The EPS can perfom a full stroke $\pm 540°$ in less than 2 seconds, the steering wheel can be set in steps of $0.1°$. This allow a reasonable freedom in doing manourvres of every kind, however if in practical applications the maximum angle is limited depending on the speed for security reasons. The steering wheel can also be controlled setting the torque. Brake and gas are jointly controlled in the range $[-10.23, +10.23]$ g even if phisical measurements show that the deceleration is less than $9 < m/s^2$ and acceleration is limited by engine and slope.

4.2 dSpace

A dSpace Micro Autobox, is placed in the trunk to accomplish all the low level control tasks. A real-time control software running on this machine, transforms the CAN message requests coming from the PCs software in CAN messages streams to be sent directly to the actuators. This module also runs the e-stop logic and the translation from and to CAN messages of the additional actuators described in 4.3 and 4.4 respectively. This module can be programmed using Matlab/Simulink tools and dSpace proprietary software.

4.3 e-Stop

An Emergency Stop system (e-stop) is operating at low level for security reasons. A radio receiver is placed on the car roof to capture signals up to 100 m from 4 different transmitters. The transmitted signal is one information bit: when signal is low (no transmission), car behaves normally and can be controlled manually or automatically; if the signal goes up when the car is in autonomous mode, the emergency system is activated and all the CAN messages coming from the computers are cut-off and a set of messages to activate brakes at their maximum strength, reduce gas and steering angle to zero are sent to the actuators with the aim of stopping the vehicle in the shortest possible amount of time. The receiver is directly connected to the dSpace module, where the e-Stop logic is also running.

4.4 Additional actuators

Some additional hardware has been installed in order to access in read and write mode some secondary actuator on

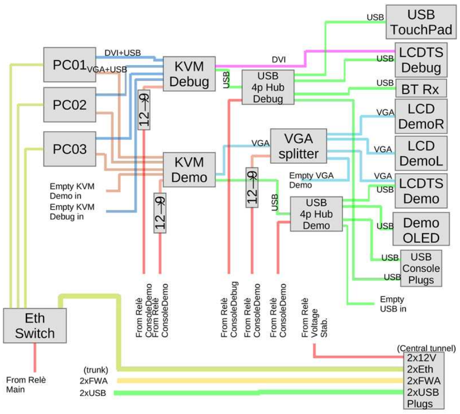

Fig. 4. Hardware and connections of the console layer.

the vehicle. All these features have been obtained using relay and wires to bring the appropriate signal in the trunk, where a custom board with relays prepare them for the I/O board in the dSpace computer where they are mapped into a set of can messages to enable the PC to read and write them.

- *Headlights.* Systems like Automatic Headlight Control (AHC) require the headlight system to be turned on and off electrically. Two controls are available. One to set if the automatic control is active or not, and one is the signal of the automatic control. When the automatic control is on, the user's decision given by the steering wheel switches are overridden by the automatic signal.
- *Indicators.* Indicators are available for reading and writing. Reading is used in systems such as lane detectors to disable warnings in intersections or maneuvers. Writing is used during autonomous driving or steering maneuvers to broadcast information outside. The reading signal is taken directly on the lamp indicator.
- *Stop lights.* Stop lights are used to signal the actions taken by the breaking system. Again, the reading signal is taken directly from the lamp.
- *Wipers.* Reading and controlling the wipers is necessary to detect weather conditions and when developing rain sensors.

5. HUMAN-MACHINE INTERFACE (HMI)

The interiors have been designed thinking of tree main purposes in mind: development, tests, demonstrations. Each of these purposes has dedicated seats and devices. A switchbox with 21 mechanical switches has been integrated in the central armrest.

Two separate consoles are available, one for debug and development and one for testing and demonstrations. The cabin area is divided in three separate zones: the driver seat is used for testing, the passenger seat for debug and development, the rear seats for demonstrations.

All changes do not impact against the car's interiors look. The debug monitor and its support, as well as the monitor cables can be removed with few simple operations. Afterwards that the car looks again like a normal car.

5.1 Touchscreen monitors and OLED buttons

Since BRAiVE is a prototype used to develop autonomous driving applications and Advanced Driving Assistance Systems (ADAS), the passenger seat besides the driver has been geared to simplify the most common task accomplished on BRAiVE: the development. A 17" touch screen is mounted in front of the user on a structure tightly anchored to the car floor (see Fig. 5, bottom left), a bluetooth keyboard is also available together with a mouse pad integrated in the internal door handle. Additional plugs allow direct connection to the PCs in the trunk of USB, firewire and Ethernet devices. The bluetooth keyboard controls one of the two KVM switches in the trunk allowing the user switching the console over the three different PCs in the trunk.

When testing ADAS applications, the driver's interface offer a 11" wide touch screen perfectly integrated in the dashboard, similar to those normally used for GPS navigation or Car Infotainment Computers (CIC) and two 8" monitors integrated in the back of the head-rests for the rear passengers (see Fig. 5, bottom left). An additional LCD monitor has been clipped over the internal rear view mirror. This monitor can be used as rear view mirror when the display is off while, when switched on, the display can show a live video coming from an analog source, like a DSP demo board or any other analog video output.

A group of 3 configurable OLED buttons is available in front of the gear lever to turn on/off applications or give commands to the system. These 3 buttons are connected and managed from one of the trunk's computers through an appropriate driver. Since the image on the button can change, images can be shown depending on the driving situation or on system past history. In this way very simple human machine interfaces can be tested, e.g. to turn on and off applications such as vehicle detection, lane departure warning or pre-crash systems.

5.2 Additional plugs

The following plugs are integrated in the upper part of the central tunnel, between gear lever and central armrest: 2 firewire, 2 USB, 2 network plugs, 2 12 V plus 2 additional USB connectors for a wired keyboard on each console remain integrated into the central tunnel structure. Still the central tunnel, in the back seat area, also hosts three additional 220 V AC plugs and the inverter's switch on button. In the trunk additional $5, 9, 12$ V and 220 V are available. A couple of additional 12 V plug has also been left free for future sensor testing in the car front, near the laserscanners.

5.3 Audio system

A 4x50W audio amplifier is available in the trunk and connected to the processing system, both for both entertainment and warning purpose. Positional audio warnings signals can be issued from the system to the driver, enhancing the user's experience with an intuitive and simplified interface. For example a lane departure warning system (LDW) can emit a sound positioned on the car side which is crossing the lane during normal driving.

Fig. 5. The Lux laser installed on the front bumper's center with the IDIS one on top of it (top left); mirror camera mounting (top right); inside view of the car (bottom left); stereo camera system and UTM-30LX laser installed on the back side (bottom right).

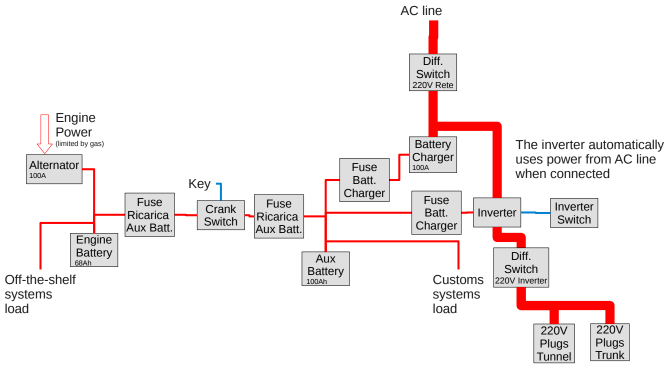

Fig. 6. Electrical System block diagram.

6. ELECTRICAL SYSTEM

BRAiVE's Auxiliary Electrical System (AES) is designed to be completely independent from the car one so that the same layout may be used over other vehicles. AES main components and connections are depicted in Fig. 6. The independence between the two electrical systems is achieved thanks to a special switch controlled by the engine key: when engine is off (e.g. usage during development sessions) the principal battery is detached from the auxiliary one, the power supply connected to the power line and the system can stay indefinitely on; viceversa when engine is on (e.g. during test or demo sessions) the auxiliary battery is connected to the car battery and power taken from the alternator. The main voltage is 12V but branches at 5 and 9 are also available through voltage regulators. An additional 220 V branch is available thanks to a 2000 W inverter being 2000 W the maximum power supported by the AES. Engine ignition is inhibited if power supply is connected to power to avoid the potential of the two batteries to be forced by the alternator and the power line.

The system is over-sized with respect of every day use which is around 25% of maximum power: 500 W. The entire AES is directly connected to a 100 Ah auxiliary battery placed in the trunk and accessible from the cabin. When the engine is off, the auxiliary battery can be recharged through the power supply, while when the engine is on charge comes from the 68 A car alternator. If the primary battery gets drained for some reason, it can be recharged using the power supply and turning the engine key in pre-ignition position. The 220 V lines are available in the trunk and in the cabin to supply additional devices such as PCs laptop or cameras with proprietary power supplies. These lines are also useful when the need of unavailable voltage arises: the appropriate power supply can be connected here. Every additional device connected to the car gets its power from the AES, its powering branch provided with an appropriate protection fuse.

7. CONCLUSIONS

The BRAiVE vehicle has been designed and set up in six months. Mounting techniques learned during the preparation are general and suitable to be adapted on any car with slight modifications of the parts directly in contact with the car itself. The vehicle has been presented to several international events. In June 2009 the prototype participated to the IEEE Intelligent Vehicles Symposium 2008 in Xi'an (China) where a live demo of the works presented in Cardarelli et al. (2009) and Cerri et al. (2009) has been shown. In October 2009, the vehicle was shown at the Conference for a Sustainable Mobility in Rome (Italy), where it carried Rome Major's while driving in Stop-and-Go mode. In December 2009, the vehicle has been shown at the MotorShow in Bologna (Italy) where a queue autonomous driving system has been shown on a close loop. BRAiVE is used every day at VisLab as a platform for research and development as well as a demonstration vehicle during visits and meetings.

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