Sensor Networks on the Car: State of the Art and Future Challenges

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***Abstract*—Modern cars are equipped with hundreds of sensors, not only used in the traditional powertrain, chassis, and body areas, but also in more advanced applications related to multimedia, infotainment, and x-by-wire systems. Such a big quantity of sensing elements require a particular attention in the design phase of the in-vehicle communication networks. This paper provides an overview of the most commonly used automotive sensors and describes the traditional networks nowadays used to collect their measurements. Moreover, it considers some possible alternative solutions that could be used in the future to have a single uniform network as asked by the automotive industry in order to reduce weight, space, and cost of the communication system.**

I. INTRODUCTION

In-vehicle communication system has been one of the most active areas of research in the automotive field over the past and current decades.

In fact, modern vehicles are required to follow strict regulations in terms of safety, pollutants, and greenhouse gases emissions, and they also need to reach a very high level of excellence in terms of comfort and energy consumption in order to meet the market needs. For example, several active and passive safety systems are already worldwide mandatory in the new manufactured car (e.g., Antilock Brake System – ABS, airbags, seat belts,…). Several other systems are widely used to prevent car accidents and will be probably as well considered mandatory in the near future (e.g., Electronic Stability Program – ESP, Adaptive Cruise Control – ACC, Forward Collision Warning – FCW, Collision Mitigation – CM, Blind Spot Detection – BSD, Lane Departure Warning – LDW, Lane Keeping Assistant – LKA,…).

In such a context, Information and Communication Technologies (ICTs) play a key role in the design and development of all the aforementioned systems. In particular, most of them require using one or more sensors, like e.g. RADAR, LIDAR, video cameras, dynamic, physical, and mechanical sensors, and others. A consistent number of sensors is also used for electronic engine management (e.g., electronic ignition systems, electronic fuel injection,…) and for comfort systems (e.g., entertainment, climate-control systems, electronic positioning of mirrors, seats, navigation systems,…). On the average, the amount of software, electric, and electronic components can reach 35 to 40 percent in total production costs of a modern car ([1]).

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The coexistence of all the developed safety systems will therefore require a huge number of sensors. The current in-vehicle networks are not adequate to handle such a big number of sensing elements. Such a problem is well known in the automotive sector ([2], [3]). A possible solution has been proposed by Yim *et al.* in [4]. They propose to manage the sensors more efficiently and to provide extensibility through a Smart Car Sensor Network (SCSN), which is an in-vehicle architecture based on AMI-C (Automotive Multimedia Interface Collaboration, [5]) and OSGi (Open Service Gateway Initiative, [6]) standards. However, that solution is still based on a traditional in-vehicle communication network like the Controller Area Network (CAN).

The current research trend is aimed at using other kind of in-vehicle communication networks characterized by better performance. In this way, it will be possible to implement innovative applications and to improve safety and reliability of the current ones. On the other hand, the use of different technologies will introduce new issues that have to be taken into account in the design phase. For example, the use of wireless communications will introduce significant security issues due to various types of cyber attacks from external entities, less present in traditional wired networks.

In such a context, this paper is aimed at summarizing the characteristics of the traditional and widely used in-vehicle communication networks and at providing some innovative solutions and applications in the same field.

The rest of this paper is organized as follows. Section II provides an overview of the sensors commonly used in the automotive field. In Section III, the characteristics of the main wired in-vehicle networks are summarized. Section IV describes some possible alternatives to the traditional communication networks nowadays mounted on cars. Finally, paper conclusions are drawn in Section V.

II. AUTOMOTIVE SENSORS

In the first part of the 20^{th} century, vehicles were not equipped with any kind of electronics and sensors. During the 1970s, electronic components started to be included and they changed the way of designing automotive systems.

This section gives an overview of the commonly used automotive sensors. As stated in [7], a modern car can be equipped with more than 100 different sensors. However, being really difficult to provide an exhaustive description of them and being also out of the scope of this paper, a list of the most common and significant sensors mounted on a car will be provided, with a classification based on functional aspects.

The automotive systems application for sensors can be divided in three areas: powertrain, chassis, and body ([7]). In each of them, the usage of sensing elements is driven by different factors, like e.g. legislation, safety, weight reduction, comfort, and convenience. In general, their wide utilization is due to the following features: miniaturization, cost reduction, increased functionality, and improved quality.

Hereinafter, a brief description of the possible applications of each kind of sensor used in the automotive field is provided, following the distinction made in [8].

Accelerometers are mainly used in two application areas: impact detection, and motion measurements. Their usage was initially driven by the diffusion of passive safety systems (in particular, airbags and seatbelt tensioners). Moreover, they also found a wide application range in other sectors, like e.g. vehicle dynamics control systems, antilock braking systems, anti-theft systems, active suspension control, and headlight leveling.

Pressure sensors have also numerous automotive applications. The main one is the air intake control. For this particular field, mass-flow sensors are typically used in order to have a better accuracy (to meet the requirements of fuel consumption and emissions). All the other usages are aimed at measuring the pressure in several components of the car (i.e., turbocharger, oil, external atmosphere, fuel-tank, brake circuit, climate, fuel, tire). According to the specific situation, the functioning range can vary from few kPa (for evaporative fuel pressure systems) to several hundreds of MPa (for diesel common-rail fuel pressure systems).

Temperature is measured in several zones of modern vehicles. In general, temperature sensors are required for powertrain performance control, diagnostic, emission control systems, and comfort equipment. The typical applications include monitoring and control of engine parameters, coolant return temperature measurement for fan-speed control, gear-box temperature monitoring, fuel temperature measurement, intake-air temperature measurement, outside-air temperature measurement, passenger-compartment temperature measurement, climate control unit parameter measurement, exhaust-gas temperature measurement before and after catalyst, and measurement of compressed-air temperature after turbo charger or compressor.

Together with temperature and pressure, the predominant sensors in use today are rotational-speed and phase sensors. Their applications are aimed at measuring wheel speed (for ABS and vehicle dynamics control), engine speed, camshaft and crankshaft phase (for motor control), and gear shaft speed (for transmission control).

Angular-rate is a recently measured quantity in the automotive field (with a particular emphasis on roll, pitch, and yaw of the vehicle). Its value is used in vehicle dynamics control systems, automatic distance control systems, navigation, and rollover systems.

Angular and linear position sensors are used to measure throttle valve angle, pedal angle or position, seat position, gear lever position, steering angle, mirror adjustment, and light adjustment to name a few. Therefore, they can be considered as the basis for the actual and future drive-by-wire systems, where pure hydraulic/mechanical control is replaced by electronic control.

Pollution legislation drives the utilization of exhaust-gas sensors. This kind of elements is present in every modern car, in order to measure the partial pressure of specific exhaust-gas components like oxygen, hydrocarbons, nitric oxide, and nitrogen dioxide.

Radar and video sensors are currently restricted mainly to luxury cars, due to the high price of these components. However, their wide usage could be very useful in order to increase the safety in modern vehicles and in general in different traffic situations, and they are able to sense the surroundings of a vehicle. In particular, RF-radar and laser-radar can be used to detect the presence and the relative speeds of objects and people, both near the car or far away from it. Video sensing can be used for the same purposes (with a low accuracy at a low cost), but its use is usually considered in more advanced systems, where scene viewing (e.g., blind spot and backup vehicle monitoring, night-vision improvement) and scene understanding machine vision (e.g., lane departure warning, lane keeping assistant, traffic sign recognition) are required.

Several other sensors are mounted on modern vehicles or will enter the market within the next few years (e.g., gas sensors for sensing air quality, telemetric sensors, biometric sensors for driver identification, electric current sensors, rain sensors, light sensors,…). However, their description is here omitted for the sake of brevity.

In conclusion, we can summarize three major statements that can be made concerning automotive sensors.

Several systems require the use of different sensor typologies in order to be properly functioning. Therefore, integration of sensors is one of the main issue to be faced with.

Moreover, their wide diffusion implies to manage them as cooperative and complex distributed systems, instead of considering them as independent parts of more ordinary systems.

The huge amount of information coming from several, possibly different, physical sensors has to be reduced by using sensor fusion and virtual sensors techniques.

III. Traditional In-Vehicle Networks

As stated before, modern vehicles are equipped with many electronic systems, not only in the traditional body control and engine management areas but also in the advanced areas of driver assistance systems and telematics applications. All of them are based on in-vehicle communication networks, and this is the reason why a lot of work has been done in such a research area.

This section is aimed at describing the main in-vehicle communication networks that have been traditionally used in automobiles. More advanced and innovative communication systems will be described in the next section.

The Society for Automotive Engineers (SAE) classified in 1994 the automotive communication protocols into three categories (from class A to C) on the basis of data transmission speed and functions that are distributed over the network ([9], [10], [11]). A fourth category (namely D) was added later on the basis of the augmented needs in terms of data rates and functionalities.

Class A networks are characterized by low data rate (less than 10 kb/s) and low-cost technology. They are mainly used to transmit simple control data related to the body domain (seat control, rain sensor, doors,…). Examples of such networks are Local Interconnect Network (LIN, [12]) and Time-Triggered Light Weight Protocol (TTP/A, [13]).
Class B networks have a data rate between 10 and 125 kb/s and are used for general information transfer (non-diagnostic and non-critical communication, such as instrument cluster, vehicle speed, legislated emissions data,…). J1850 ([14]) and low-speed Controller Area Network (CAN-B) ([15]) are examples of this class.
Class C networks are able to provide high speed real-time communications (in particular for the powertrain and the chassis domains), with data rates ranging from 125 kb/s to 1 Mb/s. High-speed CAN (CAN-C, [16]) is the main representation of this class.
Class D networks also require high speed communication (up to or higher than 1 Mb/s) and are used for telematics (multimedia, infotainment, internet, digital TV,…) and x-by-wire applications. Media Oriented System Transport (MOST, [17]), Digital Data Bus (D2B, [18]), and Bluetooth ([19]) are typically used for the first kind of applications. For the second one, Time Triggered Protocol (TTP/C, [20]) and FlexRay ([21]) are traditionally considered.

Hereinafter, a brief description of the aforementioned network typologies will be provided. Figure 1 reports a comparison among them in terms of data rates and relative cost. A more detailed survey can be found in [3], [22], and [23].

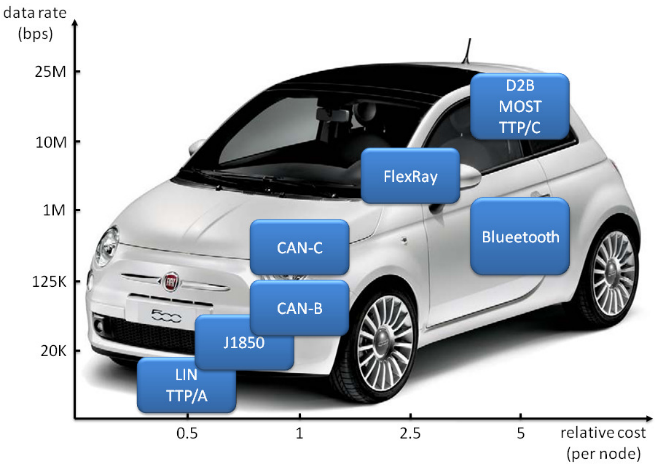

Figure 1. Data rates and relative cost for the traditional in-vehicle communication networks.

CAN is one of the first automotive control networks. It was developed by Robert Bosch GmbH in the mid-1980s. It became an ISO standard in 1994 ([15], [24]) and it can be actually considered as the *de facto* standard for in-vehicle communication network. CAN is a serial, event-triggered, broadcast bus, able to offer different transmission rates (up to 1 Mb/s), flexibility, robustness, bounded delay, cheapness, and simplicity. It implements several error detection techniques and also an energy saving mechanism (nodes sleep until a CAN message wakes them).

LIN has been developed in 1998 by a consortium composed from several car manufactures (i.e., Audi, BMW, Daimler, Volvo, and VW). It is a low cost and low speed (20 kb/s) serial communication network, widely used for body and comfort applications where versatility and data rate of the CAN are not required. LIN is organized as a master-slave time-triggered network. It is also worth mentioning that bandwidth saving and energy saving services are implemented.

TTP networks (A and C) have been developed by the Vienna University of Technology and are actually commercialized from the TTTech company. TTP/A offers similar functionalities with respect to the previously described LIN network. For that reason, it is not widely used in the automotive production. A bigger success has been earned by the TTP/C protocol, thanks to the collaboration of several companies in the TTA Group. It supports communication speeds of up to 25 Mb/s with robust fault/error confinement and error handling strategies, making it suitable for x-by-wire and aeronautic safety systems.

J1850 is an old network protocol, firstly defined in 1987 and later standardized in 1994. It has been employed for non real-time communications, in particular for the body domain and diagnostic. The provided data rate can be equal to 10.4 kb/s or 41.6 kb/s, according to the considered variant (single-wire or two-wire, respectively). Anyway, J1850 has been recently replaced by other low-cost networks (such as CAN or LIN).

MOST is a recent multimedia and infotainment network, that uses plastic optical fiber for connecting multiple devices (e.g., digital radios, navigation systems, entertainment systems, cellular phones,…). It provides a point-to-point audio and video data transfer with a data rate of up to 24.8 Mb/s. MOST development started in 1998 and it is nowadays used by BMW, Daimler, Harman/Becker, and OASIS Silicon Systems.

A similar kind of network is D2B. It provides digital audio and video data transmission with a data rate of up to 11.2 Mb/s. D2B physical layer can be an unshielded twisted pair (named SMARTwire) or a single optical fiber. Its architecture is really reliable, weight saving, and simple (just a single cable bus with few components and connectors). This standard is functional to the car during all its life time, given that it evolves jointly with devices evolution, but always providing backwards compatibility. It is used by Jaguar and Mercedes Benz.

Bluetooth is a worldwide recognized standard for low-cost, low-power, short-range wireless communication. Its application in the automotive industry has been driven by its wide diffusion among mobile phones, computers, and PDAs. The main in-car Bluetooth application is related to the possibility to use hands-free mobile phone systems in order to avoid driver distraction and increase its safety. Actually, almost all carmakers are able to offer in-car Bluetooth platforms.

FlexRay is a flexible, high-speed, redundant, fault tolerant network communication system. It has been specifically developed for x-by-wire applications from a group of companies in the automotive and electronic field. That consortium worked from the year 2000 to the year 2009 and concluded its work with the specifications of the 3.0 version. The achievable data rate is up to 10 Mb/s and the network topology can be chosen among bus, star, and multiple star, according to the specific application.

IV. New Generation In-Vehicle Networks and Future Challenges

The actual and near future trend is still to have almost dedicated buses for different applications, instead of having a single network able to cope with all the needs of the vehicle ([25]). In this way, the connecting cables have a big impact on the vehicle in terms of mass (up to 50 kg) and installation cost. The communication network of a modern vehicle is composed by several km of cables, with hundreds of connection points (usually more than 200). Therefore, that big complexity can easily lead also to diagnostic and maintenance issues.

In order to overcome such problems, the best solutions provided by the research community are based on power line and wireless communication technology. However, it is worth noting that a lot of work has still to be done in order to overcome the traditional in-vehicle communication networks previously described, both in terms of security and robustness.

Power Line Communication (PLC) technology provides data transmission over direct current (DC) battery power-line. Doing that, it is possible to reduce the number of command and control cables, giving a clear advantage in terms of weight, space, and cost. A first step in this direction was done in the late 1994 by Nouvel *et al.* in [26]. They proposed the application of the spread spectrum code division multiple access (CDMA) based on direct sequence spread spectrum (DS-SS) modulation for an automotive area network on power-lines. A renewed interest has been expressed starting from 2005, when Huck *et al.* resumed in [27] the design issues in implementing an integrated power and data transmission over the automotive power supply networks.

This kind of transmission technology reached a satisfactory level of maturity during the last decade for the residential market, making it suitable also for in-vehicle applications. However, it is worth noting that indoor domestic PLC cannot be directly applied to cars without the due modifications and adaptations. In fact, the wires architecture, the channel transfer function, and the ambient noise are completely different in the vehicle power line with respect to the home supply grid.

A large part of the research is aimed at studying the propagation characteristics and the capacity offered by the channel, and at defining the most suitable transmission techniques at physical layer. The most promising techniques for PLC transmission are aimed at counteracting the frequency selectivity of the channel, and are therefore based on the combination of CDMA and orthogonal frequency division multiplexing (OFDM). Data rates can widely vary from few to tens of Mbps, depending on the cable type and length (typically around 40 Mbps).

Despite the low cost, high data rate, and flexibility offered by PLC technology, their usage in real applications is still far away from being considered. It could be actually considered just for non critical functions, given that no redundancy and latency limitations are provided. Furthermore, additional investigations on the noise environment have to be made.

A second possible solution is represented by the wireless communication technology. This kind of solution has a great potential in terms of weight, size, and cost reduction. It also offers the possibility to place sensing elements in positions unreachable by wire. Its usage inside the vehicle has been pushed in the last 10 years from the wide diffusion of mobile phones, laptop computers, and DVD players equipped with wireless interfaces. Each specific application requires certain constraints in terms of data rate, latency, and reliability. This is the reason why it has not yet been possible to identify a single wireless standard able to cope with all the needs required in the automotive scenario. Indeed, considering that data rate is the main discriminant parameter for that kind of technologies, it is possible to classify them in two categories with low and high transmission rates, respectively.

Widespread low-rate wireless standards are Bluetooth (IEEE 802.15.1) and ZigBee (IEEE 802.15.4). The first one operates in the 2.4 GHz ISM (Industrial Scientific Medical) band with speeds of up to 3 Mbps (typically used with less than 1 Mbps in order to reduce power consumption). It is widely used to connect cellular phones, global positioning systems (GPS) receivers, and music players. The second one operates in three ISM bands (868 MHz, 915 MHz, and 2.4 GHz) at different data rates (20 Kbps, 40 Kbps, or 250 Kbps, respectively). It does not have real applications inside the modern car, but it can be considered as a viable and promising technology for implementing an intra-car wireless sensor network. Both the standards can be a good alternative to wired networks such as LIN and low rate CAN.

The only high-rate wireless standard really available for the automotive market is Wi-Fi (IEEE 802.11b/g). It operates in the 2.4 GHz band with a data rate of about 6 Mbps. Some alternatives for the same category are ultra-wideband (UWB, IEEE 802.15.3a) and 60 GHz millimeter wave (IEEE 802.15.3c) technologies. The first one operates in the 3.1-10.6 GHz band, with data rate up to 480 Mbps. The second one works in the 60 GHz ISM band, offering data rate greater than 1 Gbps ([28]). In Figure 2, it is shown a functional classification of the traditional and novel in-vehicle communication networks previously described.

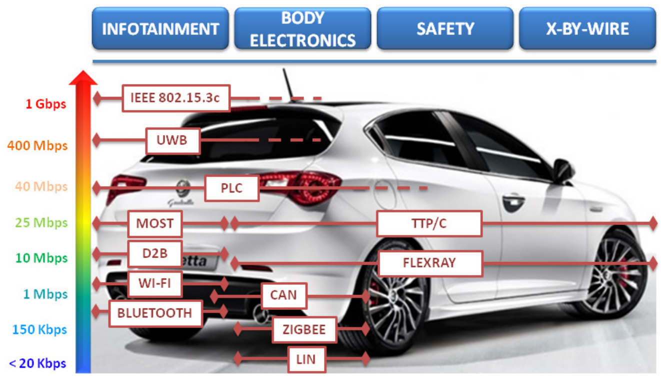

Figure 2. Functional classification of traditional and novel in-vehicle communication networks.

As stated before, only two wireless standards are really used in modern cars (i.e., Bluetooth, Wi-Fi), mainly for multimedia and infotainment applications. However, the main application of this kind of technology will be probably related to sensing aspects, given that the next generation of wireless sensors is characterized by low power consumption, small size, long duration with batteries, and easiness of installation. A big push in this direction has been given in United States since 1 September 2007, when tire pressure monitoring systems (TPMSs) became mandatory for every new sold vehicle ([29]). Besides that, a lot of work is being done by private and public research centers in order to apply wireless sensor technologies in the automotive field, and some research projects are being funded on the same topic.

For example, the European Union is funding a research project named CHOSeN (Cooperative Hybrid Objects Sensor Networks) ([30]). Its target is to develop application-specifically adaptable communication technologies enabling the real deployment of smart wireless sensor networks in large-scale, for performance-critical application fields like the automotive and the aeronautic. In the framework of the first application scenario, a certain number of sensors has been wirelessly integrated on the car, in order to measure different parameters (e.g., braking circuit pressure, braking disk temperature, road temperature, external lighting level, external air humidity and temperature, tyre temperature and pressure,…). All the sensors are organized in a wireless sensor network (WSN) able to collect the acquired measurements and making them available to a central unit through an interface to the traditional CAN bus, eventually after the application of data fusion algorithms on part of them. The collected data are then used to assist the advanced driver assistance system (ADAS) in detecting dangerous situations.

It is worth highlighting that each wireless interface mounted on the car can be considered as an entry point for cyber attacks to the in-vehicle network ([31], [32]). However, also traditional wired networks suffer of security issues ([33]). This is the reason why recent research activities are focusing also on in-vehicle security ([34]).

V. Conclusions

In this paper, the topic of the in-vehicle communication networks has been treated. At the beginning, an overview of the commonly used automotive sensors has been provided. After that, the characteristics of the main traditional wired in-vehicle networks and some possible alternatives to them have been summarized. The interest of the research community in these topics is related to the concept of having a uniform network in each car, as supported by the automotive industry. However, the proposed solutions are still not able to cope with such a target.

Future research works should be devoted to the definition of a single technology able to cover all the specifications required by the applications nowadays implemented on the cars. Moreover, they should cope with the security issues arising from networking aspects.

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