Drive-by-wire systems for ground vehicles

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Drive-by-Wire Systems for Ground Vehicles

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Abstract — **A significant innovation effort in present ground vehicles' technology is represented by the replacement of the traditional mechanical-hydraulic systems with all-electric systems, termed by-wire systems, for the transmission and execution of the driving commands. According to the experience in the aerospace environment, such replacement is expected to give appreciable benefits, even though it poses several problems. This paper provides an overview of the key components of by-wire systems, i.e. the electric actuators and the communication networks, especially for steering and braking operations.**

Index Terms — **By-wire systems, automotive applications, electric actuators, communication networks.**

I. Introduction

Electric solutions for the transmission and execution of driving commands are already employed in many transportation means. An example is represented by the fly-by-wire systems, nowadays implemented on board of large airplanes. Although here hydraulic actuators commanded by electric valves often deliver the power for executing the commands, the application of fly-by-wire systems is evidence of a trend towards the all-electric airplane. By-wire systems are also employed in the naval environment and on board of trains and metros. Their application has been prompted by the significant benefits deriving from the replacement of the traditional mechanical-hydraulic systems with electric systems: higher efficiency, lower maintenance requirements, better dynamic response and accuracy, much higher overall design flexibility, far easier integration with control and monitoring systems, unprecedented levels of drive assistance functions, and so on. It has been also demonstrated that the adoption of suitable design criteria with adequate levels of fault tolerance and redundancy can give the electric systems reliable performance and fail-safe capabilities even better than the traditional systems.

In the above-mentioned environments, the acceptance of by-wire systems was facilitated by the relatively limited incidence of their cost with respect to the prize of the vehicles. The situation is different for the production-model cars because of their much lower prizes and of the highly cost-sensitive market. Moreover, airplanes, ships and trains are complex vehicles operated and maintained by professional personnel while the passengers are not concerned with the technical arrangement of the vehicles and, as for the journey safety and the means efficiency, rely on the ability of the crew. The opposite occurs for the motorcars since in most cases the owner drives them. This makes him conscious about guidance and maintenance of the vehicle and requires his involvement in the new way of "driving by wires". The distinct scenario has determined on one hand a slower introduction of by-wire systems in the car environment and, on the other hand, their usage mainly for carrying out tasks non related to the driving commands. In the last years, however, by-wire commands are gradually migrating from the racing cars to the special-model ones and, furthermore, have been perceived as a natural milestone closely preceding the transition towards hybrid and electric vehicles [1]. Consequently, all the car manufacturers have turned their interest on the by-wire systems and have launched important research programs that have already led to the conception of futuristic cars implementing the full by-wire idea.

In this paper the main features of the key components, i.e. the electric actuators and the communication networks, of the by-wire technology intended for the car environment will be presented, focusing on the steering and braking operations. A detailed description of the two types of components may be found in [2] and [3], respectively.

II. System Structure

By-wire systems have been conceived to replace the traditional means for the fulfilment of the commands directly concerning with the vehicle driving, i.e., throttle, gear-change, steering and braking. In particular, a communication network substitutes for the transmission linkages and the electric actuators for the mechanical ones.

The critical commands for a by-wire systems are steering and braking and around them is focused the paper.

Fig.1 shows an example of structure of by-wire system that includes four brake-actuator units and a steer actuator unit. Each actuator unit, located next to the engaged mechanical parts (e.g., wheels or brake callipers), is composed of an electric actuator fed by a static converter. A central unit using strategies that account for the driving commands, the vehicle current state and the environmental conditions governs the actuator units. Steering and brake commands are transduced and then entered into the respective units (e.g. brake-pedal and steer–wheel units). Communication networks link the various units. Differently from the data transmission supporting to non-critical car functions, the communication tasks bringing the driving commands are

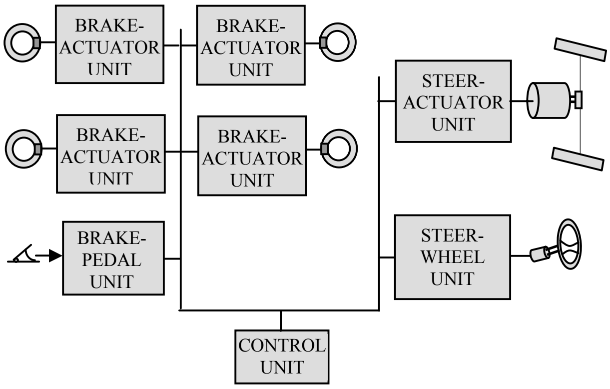

Fig.1. Example of braking and steering by-wire system.

much more demanding in terms of determinism, fault-tolerance and reliability of the communication. Development of by-wire systems must comply with both cost and safety-critical targets [4]. This entails a careful design of the components in order to get a satisfactory trade-off between device quality, system redundancy and economies due to large-scale production.

III. ELECTRIC ACTUATORS

A. Steer-by-wire actuators

According to the classical Jeantaud configuration, in traditional ground vehicles the steering capability is provided by the foremost wheels, which can be rotated around a grossly vertical axis by means of a transversal bar linking them. In some cases, e.g. for heavy trucks and industrial vehicles, the rearmost axle is also or alternatively used for the same function. The steering angle is directly determined from the pilot by turning the steering wheel, which drives the transversal bar through the steering column and a pinion coupling. To reduce the correlated physical effort, several years ago steering-assistance systems were introduced. They usually feature a purely hydraulic or pneumatic nature, are directly powered from the engine, and operate on the steering column as torque amplifiers. Nevertheless, their efficiency is low: therefore, since a few years electric steering-assistance systems (e.g. [5, 6]) have been introduced in the market, also permitting to save on weight and volume. Presently, such systems simply include a permanent-magnets d.c. motor gear-coupled to the lower part of the steering column, below a calibrated portion whose deformation is sensed to estimate the torque exerted by the pilot. Different types of rotary electric actuators have also been considered for such application, to further reduce the manufacturing cost and the maintenance requirements. Recently, the employ of drive-by-wire systems has been introduced to provide an automatic steering capability for the rear axle, especially for sport-utility vehicles (e.g. Fig.2). Such systems, using solutions developed for servo-steering, are able to adjust the rear steering angle depending on the vehicle speed and on the front steering angle, which is still directly determined by the pilot in mechanical way. This solution permits to appreciably reduce the turning ratio at low speed while improving the stability at high speed.

When considering the transition from servo-assisted to steer-by-wire systems, several issues have to be examined. First, an accurate evaluation of the risks-benefits balance has to be carried out about the presence of a mechanical connection between the input device, e.g. a classic steering wheel, and at least one pair of direction wheels of the vehicle. In fact, serious accidents might occur when no means are provided to keep the vehicle in control in case of sudden complete failure of the drive-by-wire system. Anyway, currently such risk is reputed acceptable in avionic ambit thanks to the high reliability levels achieved through an appropriate redundant design. Moreover, keeping mechanical connections might augment the risk of injury in case of crash accident. A second issue concerns the number of direction wheels and the mechanical linkage between them. In fact, on one hand the present electric servo-drive structure might be converted into a pure by-wire system by simply removing the steering column. In this case, collector-less rotary a.c. motors, driven through converters, may be employed to lower costs and to eliminate the maintenance-reliability problems of brushed motors. Alternatively, either a linear motor, or a rotating machine coupled to a ball-screw device, may be employed to directly operate the transversal bar, eliminating the pinion coupling. In this case, short stroke linear a.c. permanent magnets or reluctance machines may provide interesting performances and weight-volume savings, while induction machines may constitute a cheaper solution. A more innovative solution may consist in removing the transversal bar wheels and using a separate actuator to determine the angular position of each direction wheel. This solution allows turning each wheel into a direction wheel, achieving then an unprecedented driving flexibility. When properly exploited, such flexibility might then notably improve both the vehicle performances and its active safety. A first possible implementation consists in using either linear actuators, or rotary motors coupled to ball-screw devices, to determine the steering angle by laterally pushing or pulling the wheels with respect to their suspension axes. In this case, short-stroke a.c. machines may constitute an interesting solution. Alternatively, rotary motors might be used to turn the suspension axle of each wheel, directly or through a gear coupling, thus determining the steering angle.

Fig.2. Electric rear steering.

Fig.3. Electric brake unit.

Such solution might permit to achieve much wider rotation ranges, notably reducing the turning radius and permitting manoeuvres presently impossible, e.g., on-site turning or even lateral parking. In a steer-by-wire system, the most conventional choice for the input device consists in a steering wheel connected to a suitable angular position sensor, whose output is sent to the central management unit as a reference signal. The steering wheel might be also connected to a torsion spring to achieve a safe self-alignment behaviour towards the mean straight-drive position and to let the user feel a reaction torque increasing with as turning radius decreases. Such simple inexpensive solution is well suited for vehicles operated at mid-low speed on even pavements, i.e., not requiring prompt reactions from the pilot. In this case, the same basic principle may be easily applied to different types of input devices, e.g., a cloche or joystick. For more demanding applications, it is generally assumed that the pilot may stay better in control when he feels through the steering wheel an effort correlated to the steering torque actually applied to the wheels. In this case, the most suited input device remains probably the steering wheel, since it could be simply coupled to a rotary motor suitably driven by the central management unit to provide the desired feedback. For such application, when a multi-turn capability is required the best suited typology of drive would be probably constituted by an inverter feeding permanent magnets synchronous machine, able to minimize weight and volume. Moreover, the potential presence of 2 angular sensors, for acquiring the reference position and for the drive control, might be exploited to provide the required redundancy. On the other hand, when small maximum turning angles were required, short-stroke rotary actuators might constitute a less expensive alternative.

B. Brake-by-wire actuators

In classical vehicles, the braking function is performed in dissipative way by pressing friction pads on metallic disks or drums through hydraulic pistons, which are directly activated from the pilot through the brake pedal. Usually, for safety reasons, the hydraulic circuit features some redundancy while a partial servo-braking function is provided from the engine in indirect mechanical way to reduce the physical effort required to the pilot. In the last few decades, active safety systems have been introduced to improve the braking effectiveness, such as ABS, and the vehicle stability, such as EBD, in emergency conditions. Basically, such systems include an electronic management unit plus, per each wheel, a speed sensor and a fast electric valve able to adjust the braking torque. During emergency braking, the control unit drives the valves to keep each wheel close to the blockage-slipping condition yet avoiding this situation, maximizing so the braking effect. A dynamic stabilization action can be also achieved by applying more sophisticated strategies.

For brake-by-wire systems (e.g. Fig.3), a first important aspect concerns the possible presence of a mechanical structure permitting the pilot to directly perform a braking action, as a backup in case of sudden complete failure of the electric system. Such solution might improve the safety level and the acceptability of brake-by-wire systems, although increasing the overall complexity. Anyway, a purely mechanical subsystem should be probably kept for stationary braking, to avoid using active devices consuming energy to perform such non-dissipative task. Such subsystem might be then designed to act also as emergency backup of the by-wire system, permitting an overall optimised design. A second significant aspect concerns the actuation system: in fact, the primary forces required for friction braking are very high, although they have to be developed along very short strokes.

Therefore, it might be difficult to design linear electric motors able to provide such forces while complying the low cost, weight and volume targets typical of automotive applications (e.g. [7]).

Simple mechanical leverages could be then used to reduce the force required. For such solutions, the most promising typologies are longitudinal motion mono-phase reluctance machines, which can leverage on the short length of the strokes and may even use bulk iron parts with high induction levels. In fact, the short stroke, joined with usually slow dynamics, should determine acceptably low parasitic currents. Anyway, permanent magnets may be also suitably introduced in the design to further improve overall performances. A different solution may consist in employing a rotary-to-linear adapter, such as a ball-screw device, to convert a low torque into an appropriately high force. Such devices may then permit using inexpensive small-size rotary motors, although the overall dynamic performances could be reduced according to the force/torque ratio used, and a more complex static converter may be required to drive the motor. Moreover, ball-screw devices require a frequent maintenance and make the braking system more complex and less reliable. Alternatively, indirect electro-hydraulic structures could be considered to act the brakes: such solutions might permit to use the same valves and pistons manufactured for present systems, but requires to keep the hydraulic pressurized circuit, increasing so the complexity and maintenance requirements while lowering the overall reliability.

For what concerns the pilot interface, the most conventional input device for the braking command consists in a pedal, which may be contrasted by a simple linear spring. The position of the pedal, sensed by a suitable linear sensor, is transmitted to the central management unit to determine the braking request. When necessary, in the final part of its stroke the pedal could also directly activate the mechanical backup braking system for emergency situations. Alternatively, different input devices might be considered, ranging from hand leverages joining the braking and throttle commands to integrated cloche-like devices managing also the steering command. Nevertheless, such solutions would be clearly less suitable to implement a mechanical emergency braking linkage. In any case, the presence of a suitable spring may provide a sufficient feedback sensation for the pilot: in fact, probably a true feedback proportional to the actual braking action would provide a modest benefit, not justifying the correlated cost.

IV. COMMUNICATION NETWORKS

Three communication networks meet the requirements of the by-wire applications. They are designated with the names of Time-Triggered Protocol (TTP) [8], FlexRay [9] and Time-Triggered CAN (TTCAN) [10]. The first network has been developed by the University of Vienna for the data exchange in real-time distributed systems [11], the second one by a pool of car companies on-purpose for by-wire applications whilst the latter one is an evolution of the CAN networks [12]. All the three networks utilize the Time Division Multiple Access (TDMA) method to make the network behavior deterministic. In contrast to the more popular event-triggered method, the access to the bus with TDMA is marked by the passing of time or, as it is commonly said, is time-triggered. TDMA implementation needs that all the nodes of the network share the same time reference, which becomes the global time of the network, and know at every time instant the node having the right of accessing the bus. Each node, moreover, has the right of transmitting a data frame within a fixed time. These regulations avoid the occurrence of collisions between the messages and ease the identification of a malfunctioning node engaging the bus at a wrong time instant or failing in transmitting its data frames. Since most of the applications need a communication task running in a periodic way, all the three networks handles the node activity accordingly.

In TTP and FlexRay the safety requirement is achieved by means of mechanisms of error recognition and fault recovery whilst the fault-tolerance requirement is met by the duplication the physical channel and the built-in management of the transmission over the two channels. TTCAN, instead, has a much simpler structure that does not provide for duplication of the physical channel and leaves the fault management to the application software. The three networks are illustrated below.

A. Time-Triggered Protocol

TTP protocol divides the time into elementary intervals called time slots. During a time slot, only one node is entitled to access to the bus and transmits only one data frame. The time slots are gathered into a group, termed TDMA round, and their succession within the round establishes the sequence of the nodes in accessing the bus. The nodes are ordered in the set-up stage of the network and the same order is usually maintained in assigning the time slots within a round. The rounds may differ in the number of time slots and in the data frames sent by the nodes. The rounds, in turn, are grouped into a so-called cluster cycle that is repeated periodically. Fig.4 exemplifies a cluster cycle and details three rounds with the first slot assigned to node A.

Every TTP node is endowed with its own MEssage Descriptor List (MEDL), which is a memory segment organized in the form of array.

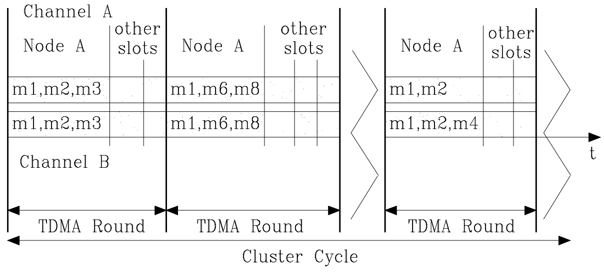

Fig.4. TTP cluster cycle.

Each row refers to one time slot of the cluster cycle and is drawn up at the network set-up with parameters relevant to the data frame that has to be transmitted. A MEDL row contains the starting transmission time of the data frame, the storing address of the messages in the dual-port RAM that interfaces the device controller of a node with the communication controller, and some data frame attributes. A node accesses the bus whenever the global time equals the starting transmission time stored in the current MEDL row and the pertinent data frame is set as an output for that node. Moreover, by comparing the arrival time of the received frames with the scheduled times stored in MEDL, all the network nodes adjust their local clocks so that the coherence of the global time is maintained. MEDL can store data relevant to more cluster cycles. This enables TTP to modify the transmission task, termed communication mode, by changing the cluster cycle in use. The change must come into force simultaneously for all the nodes and is accomplished by setting some bits in the header of the data frame.

TTP has two types of data frames: Normal frames (N-frames) and Initialization frames (I-frames). The N-frames contain the messages whilst the I-frames are utilized to synchronize the network operation and to manage transmission errors and faulty nodes. Their format is similar to the N-frames, with the exception that the data field contains the state of the communication controller (C-state), instead of the messages.

The C-state is formed by the global time, the index of the current MEDL entry and the membership vector. The latter one is a string of bits, each of them belonging to a specific node. The value of the bits indicates whether the corresponding node has sent a correct message (state 1) or not (state 0) in the previous round. Whenever a node detects that its bit in the received membership vector is 0, suspends the transmission and starts the procedure of reconnection to the network. By help of the membership vector, errors and faults are detected. When a network operates correctly, all the nodes agree on the content of the membership vector sent by transmitting node. A prompt check of the network operation could be obtained by encapsulating the membership vector in the N-frames, but at the expenses of an extension of the transmission times. TTP overcomes the problem by appending the membership vector to the data field of the N-frames only for calculating their CRC; the receiving node, in turn, appends its own membership vector to the received data frame and calculates the relevant CRC. If the local CRC coincides with the received one, the message is believed to be arrived undamaged and the membership vector of the two nodes to be equal; otherwise, either a transmission error occurred or the membership vectors were different: in both the cases the data frame is discarded.

TTP protocol has been implemented on several physical layers with transceivers meeting CAN, RS485 and Ethernet standards and using both copper cable and glass fiber as a transmission medium. The maximum transmission speed with CAN transceivers is of 1 Mbit/s; with asynchronous and synchronous communications of 5Mbit/s and 25Mbit/s, respectively. A specific physical layer is near to be released, aimed at achieving higher transmission speed and compatibility with automotive 42 Volt power supply.

B. FlexRay

FlexRay protocol utilizes, in addition to the time-triggered bus access method, the event-triggered one, sharing the communication bandwidth between the two types of transmissions. The time is divided into communication cycles that, in turn, are made up of two segments, termed static and dynamic. The static segment supports the time-triggered transmission and is divided into time slots long enough to include one data frame. Within a segment, a node sends a data frame every time the slot counter matches the identifier assigned to the frame. A static segment is exemplified in Fig.5, where DF stands for data frame and ID for identifier.

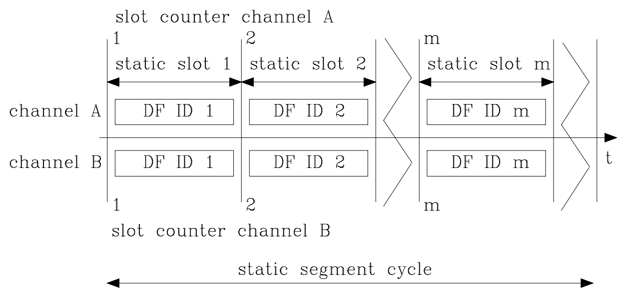

Fig.5. Static segment.

A dynamic segment is divided into minislots, which are time slots shorter than those of a static segment. A node wishing to send a data frame is entitled to access the bus only when the identifier of the data frame matches the minislot counter. Being the time required to send a data frame greater than the minislots, their count is stopped during the transmission of the data frame and carried on when the bus becomes again idle, as shown in Fig.6.

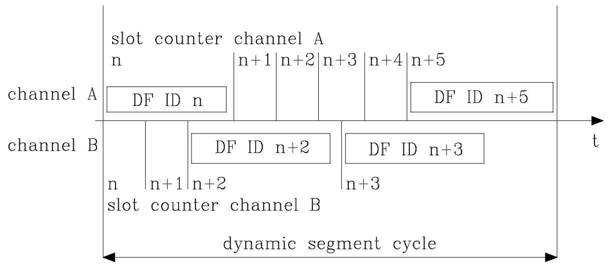

Fig.6. Dynamic segment.

Since each data frame has its own identifier, collisions during the dynamic segment are avoided and priority in the data frame transmission is ruled by the order of the identifier. Static and dynamic segments utilize in distinct manner the two transmission channels. During the static segments the same data frames are transmitted on both the channels while during the dynamic segments the two channels are used disjointedly so that different data frames can be transmitted at the same time. The reason is that the dynamic segments are typically used to deliver non-critical data frames.

Each node of the network is informed at the set-up stage of the time slots assigned to its data frames whilst it learns the association between time slots and data frames of the other nodes step by step, by monitoring the traffic on the bus.

Network synchronization, required for the time-triggered bus access during the static segments, is accomplished by means of synchronization frames sent by dedicated nodes according to a fault-proof procedure.

In FlexRay the only type of error handled by a node is the failed synchronization of the local time with the global time. As soon as an error occurs, a counter is updated and the result is compared with two thresholds. When the lower threshold is exceeded, the node suspends the transmission but continues to receive the data frames and attempts to synchronize with the global time; in case of success, the error counter is zeroed and the node resumes the normal operation. In the opposite case, when the upper threshold is reached, the node removes itself from the network and can be rebooted only by user application.

FlexRay protocol is independent of the physical layer, the only constraint being the transmission frequency of 10 Mbit/s. A specific line driver is under development; in the meantime, the RS485 standard is used. Another feature of the physical layer is the usage of a reliable process of bit acquisition that copes with the possible corruption of the signal due to the electromagnetic noise.

C. Time-Triggered CAN

TTCAN protocol enhances CAN with communication services aimed at achieving a deterministic and periodic behavior. The time arrangement is similar to TTP whilst, like FlexRay, the bus access is both time-triggered and event-triggered. The time is divided into time slots, each of them assigned to a node for the transmission of only one data frame. The time slots are gathered into a basic cycle and their succession within the basic cycle establishes the sequence of transmission of the data frames. The first slot of the basic cycles is allocated for a data frame with a particular message, termed reference message, broadcasted by a central synchronization node. In addition to start the basic cycles, the reference message synchronizes the clock of all the nodes of the network. Some time slots, termed arbitration windows, are devoted to the event-triggered transmissions, with the nodes that contend for the medium according to the CAN access method, i.e. according to the Carrier Sensing Multiple Access/Collision Avoidance method. To support this access, the bus drivers and the

transmission frequency (1 Mbit/s) of CAN are maintained.
The basic cycles have an equal number of time slots but may differ in the number and type of data frames and in the number and allocation of the time slots with event-triggered transmissions. More basic cycles can be linked together and repeated in a cyclic way, forming the so-called system matrix shown in Fig.7, where RM stands for reference message and AW for arbitration window.

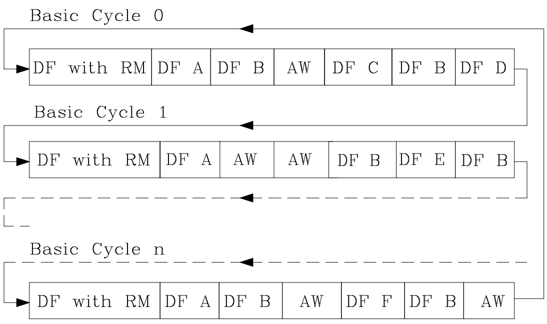

Fig.7. TTCAN system matrix.

The association of the time slots to the nodes and the structure of the system matrix are stored in a scheduling table resident in every node. Basic cycle, system matrix and scheduling table play the same role as TDMA round, cluster cycle and MEDL in TTP.
It is worth to note that the CAN networks are not able to accommodate for the TTCAN protocol because they do not dispose of the hardware for implementing the scheduling table, the synchronization circuit and the algorithm for their management.

D. Protocol comparison

TTP is endowed with powerful functions for error detection and recovery from temporarily faulty nodes but does make provision for the transmission of sporadic messages. On the contrary, FlexRay exhibits a good disturbance rejection and the capacity of handling event-triggered transmissions. Concerning the transmission speed and the frame overhead, TTP is faster and more efficient than FlexRay. However, for by-wire applications, where the updating interval of the driving inputs is of a few milliseconds, the transmission speed of both the networks appears adequate whilst the items of noise insensitivity and flexibility are favor of FlexRay.
TTCAN has the merits to be cheaper and of easy implementation, especially for system developers with a good knowledge of CAN networks. Then it represents an attractive choice for the industrial vehicles cruising at low speed and in closed sites since they do need neither a high transmission speed of the driver commands nor a sophisticated fault management.

V. CONCLUSIONS

Within a few years, ground vehicles will be extensively equipped with by-wire systems in place of the mechanical and hydraulic apparatuses for the transmission and execution of the driving commands. The combined use of electric actuators, fail-safe communication networks and powerful control units will yield a number of benefits; among them the increase of the performance and the energy efficiency of the vehicles, the intelligent management of the driving commands and the improvement in the passive and active safety of the driver (and the passengers). Such an evolution will represent an important milestone in the automotive history and will complement the expected trend toward the hybrid or the purely electric vehicles. This paper presented an overview of the main features of the electric actuators and the communication networks for by-wire systems, mainly referring to steering and braking functions.

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