A Modular Control Architecture for a Small Electric Vehicle

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Abstract

This paper presents a fault-tolerant modular control architecture for an electrical vehicle (VEIL) equipped with x-by-wire sub-systems. The proposed architecture is based on COTS components and includes steer-by-wire, brake-by-wire and accelerate-by-wire safety critical functions. The communication infrastructure is based on the FTT-CAN protocol, which provides the joint scheduling of message and tasks, according to a holistic approach.

1. Introduction

Small electrical vehicles contribute to reduce air pollution and increase the mobility in urban areas, are more energy efficient and economic to operate and, at least in some aspects, present a better performance when compared with conventional internal combustion-based vehicles. VEIL (license free electrical vehicle) is a project undertaken by ISEC (Instituto Superior de Engenharia de Coimbra) and aims at designing a license free electrical vehicle [1], integrating automatic control functionalities, namely break, steer and accelerate-by-wire systems.

The adoption of x-by-wire technologies brings sizeable benefits to the automotive systems, permitting important weight and cabling reduction, increased flexibility and maintainability and has the potential to permit a more efficient energy usage, with a noticeable impact on the operational costs and pollution reduction.

With the introduction of x-by-wire systems, mechanical sub-systems are being replaced by electronic systems incorporating sensors, ECUs (Electronic Control Unit) and actuators, interconnected by dependable real-time networks. Due to safety reasons, the former x-by-wire systems were coupled with mechanical backups, which assured the subsystem operation in case of failures of the electronic subsystem. However, the gap of performance between the mechanical and the electronic systems has increased drastically, leading to a situation in which the drivers cannot cope with the non-assisted system in a safe way. Furthermore, the inclusion of the mechanical backup systems conflict with typical constraints of mass production like low cost, reliability, modularity and maintainability. Consequently there is a trend to abandon the use of mechanical backups, leaving the entire responsibility to the electronic subsystems. In these environments the x-by-wire systems are safety-critical [2] and, thus, require adequate fault-tolerance mechanisms [3], particularly the break and steer-by-wire systems.

Replication and redundancy are commonly used to provide fault-tolerance in safety-critical systems, to achieve continued service despite the presence of faults. In this work we propose the use of FTT-CAN [4] protocol and some components of its associated fault-tolerant architecture [5] as the basic building block of the overall x-by-wire system.

The reminder of the paper is organized as follows. Section 2 presents the related work. Section 3 describes the main characteristics of VEIL. Section 4 presents the functional level description of the proposed architecture. Section 5 describes the modular distributed architecture and, finally, Section 6 concludes the paper.

2. Related work

The first x-by-wire functionality implemented in a vehicle was the throttle-by-wire included in the Chevrolet Corvette series in 1980. Nowadays these technologies become a commonplace, with most road vehicles incorporating a mix of x-by-wire functionalities. For instance, the Toyota Prius features electronic throttle, brake and transmission control.

The design verification and validation of x-by-wire systems is complex, involving mechatronic components, networks, ECUs, cabling, interactions with the power system, etc. Currently, there are several active projects to design x-by-wire functions. Notable examples, more focused in methods and techniques for steer-by-wire control, are described in [6][10][11][12]. Langenwalter et al [9] proposed a virtual design process for x-by-wire systems using IQbus™ design environment and the Saber® simulator, aiming at providing designers with a tool to manage the design, prototype, and tests of the
systems in a virtual environment. The design of a break-by-wire system is used as an example. The BRAKE project [8], a partnership between Delphi Automotive Systems, Infineon Technologies, Volvo Car Corporation and WindRiver, aimed to design a distributed brake-by-wire system with open interfaces with OSEK extension and fault-tolerant support.

A general requirements analysis for by-wire automotive systems is presented in [2]. This document, resulting from an Esprit research project, also details the dependability analysis of future by-wire applications.

An impairment to the widespread adoption of by-wire technology in mass production vehicles is the power and cabling issues related with traditional 12V batteries. However, recent and promising advances in 42V battery technology will solve this problem [7].

3. VEIL Platform

The aim of the VEIL project has been the conversion of a small vehicle based on an Internal Combustion Engine (ICE) in to an Electrical Vehicle (EV).

The chosen model was a LIGIER 162 GL, which has small dimensions, thus ideal for urban traffic, with two seats and a luggage volume of 400 dm³. The original engine was a Lombardini 4 stroke diesel engine, with 505cc, 5.4hp, maximum rotation of 3100 rpm and 15.1 Nm (at 2340 rpm).

Some of the more desirable characteristics of an EV motor are simple operation, compactness, good electrical efficiency, excellent reliability and minimal maintenance. According to these characteristics and to the present development state of the induction motors (IMs) and Variable Frequency Drivers (VFD) it was chosen to use an industrial IM-VFD with vector control strategy, working in the four quadrants. Santos et al [1] present simulation results of the chosen IM-VFD in the vehicle dynamics.

The fuel tank was replaced by a pack of NiMH batteries with 96V and it is planned in the near future to use a super capacitor to exploit the regenerative braking. The VFD is fed directly through its DC link with a bidirectional DC-DC chopper to raise the voltage of the batteries to the VFD compatible level (550V - 800V).

4. Functional Architecture

VEIL is based in a fault-tolerant modular control architecture. Besides the by-wire functions, the vehicle also includes a set of support functionalities that implement the user interface and the global energy management.

Figure 1 presents the ECUs needed to satisfy the vehicle requirements, including the data flows that each ECU produces and consumes.

4.1. Brake-by-wire

The brake-by-wire system is responsible by transmitting the driver’s brake intention to the brake actuators positioned on each wheel. Electro-hydraulic brake-by-wire systems still use conventional hydraulic brake callipers at each wheel, but with the hydraulic pressure being controlled by one ECU.

This system is composed by a brake pedal and associated angle sensor, and set of brake actuators composed by the park brake actuator, brake fluid pressure sensor and brake fluid hose, connected to the hydraulic brake calliper. The brake-by-wire system may also gather data from other subsystems, namely the wheel speed, steering angle, yaw rate and lateral acceleration sensors to determine the optimum amount of brake pressure to apply at each wheel, thus decreasing the braking distance and increasing the safety.

Each wheel has an independent braking subsystem and the hydraulic pressure is applied independently on each wheel. The breaking system operates in two modes. Initially it is used the IM-VFD in regenerative braking mode, with the produced energy being collected by a super-capacitor to charge the batteries. When this actuation is not enough to reduce the vehicle speed at the rate desired by the driver, the electro-hydraulic actuators above described are activated.

The system involves the use of two ECUs, one that senses the position of the break pedal (pos_brk signal) and other that implements the break strategy, namely the activation of the electro-hydraulic components, the amount of pressure to apply on each wheel and the implementation of the ABS (Antilock Braking System) algorithm. The individual control and sensing of each wheel is carried out by specific ECUs interconnected by a subnetwork.

4.2. Steer-by-wire

The steer-by-wire system is composed by the steer wheel angle sensor, the steer wheel feedback motor, the pinion angle sensor (wheels angle) and the steering motor. This system is physically broken in two complementary subsystems, each managed by a distinct ECU. One of the subsystems is devoted to the steering wheel handling, namely the interface with the angle sensor (ang_sw signal) and control of the feedback motor, whilst the other subsystem interfaces with the road wheels sensor (ang_whl signal) and controls the steering motor.
The system implements some desired control strategy as proposed in [6] with a set of filters that convert the hand wheel angle to torque applied to the steering system and a PD controller that tries to minimize the steering error between the hand wheel and the pinion angles.

The simulation of this steer-by-wire architecture, without including the fault tolerance aspects, is presented in [13]. Currently the filters of the hand wheel node are partially implemented, only.

4.3. Accelerate-by-wire

Most conventional internal combustion vehicles include a throttle position sensor (TPS) to provide input to diverse subsystems like traction control, ABS, etc., having a mechanical link to connect directly the pedal with the throttle control. In these cases, the throttle-by-wire system replaces the mechanical link, using one ECU to compute the required throttle position from data measured by other sensors such as the accelerator pedal position, the engine rotation speed, the vehicle speed, etc. The throttle control is then driven to the required position by the ECU, typically using a closed-loop control algorithm.

VEIL uses a similar architecture, but with the actuation carried out on the VFD instead of a throttle. For this reason the system is called the accelerate-by-wire and is composed by the pedal position sensor, motor drive and electrical motor (Figure 2). The accelerator pedal sensor is attached to one ECU, which disseminates the pos_acc signal. The effective control of the motor is carried out by a dedicated ECU connected to the IM-VFD.

4.4. Dashboard panel

The dashboard panel provides the driver with all the relevant information about the vehicle conditions. It is based on an intelligent device (a PalmOS, in the case) and can present both raw information (e.g. vehicle velocity, motor current, voltage of low-voltage dc-link, batteries energy, etc) as well as integrate the data to provide information like autonomy, trip length, average speed etc.

It is also possible to set alarms related to some variables, e.g. when the battery energy lowers below a given threshold.

4.5. Energy Management System

VEIL has several energy sources that require appropriate management. A specific ECU is devoted to control the energy flow between the sources – batteries, super capacitors and solar panels – and the motor, with the objective of maximizing the autonomy, assure functioning parameters within bounds (e.g. continuous control of batteries state of charge) and to provide maximum longevity of all subsystems.
4.6. Communication Requirements

Steer and brake-by-wire functionalities are safety critical. Furthermore, many of the x-by-wire systems include close-loop controllers, which are particularly sensitive to jitter and end-to-end delays. For these reasons, it was decided to use the FTT-CAN protocol [4] as the communication infra-structure.

The fault-tolerance aspects are addressed in the next section. Regarding the jitter and end-to-end delays, the use of a time-triggered protocol like FTT-CAN permits to impose phase control both on the system tasks and messages. With a proper analysis this level of control may be used to synchronize appropriately the several steps that each operation requires (e.g. sampling, set-point computation and actuation), thus minimizing the end-to-end delays. An illustrative example of the use of these features of the FTT-CAN protocol, applied to a middle-size soccer robot, can be found in [19].

In order to use FTT-CAN in VEIL it is necessary to identify the flow of messages between the ECU, their priorities, periods, sizes and relative phasing. Table 1 presents these communication requirements. Different messages issued by the same node with the same activation period were piggybacked into a single message (column Frame ID in Table 1).

The elementary cycle duration was set to 5 ms which is the shortest period among all periodic activities and messages. From the requirements stated in Table 1 results a bus load is close to 24% for a CAN at 250 Kbps, which is feasible.

5. Fault-Tolerant Modular Architecture

This section presents the fault-tolerant hardware architecture and the underlying fault hypothesis.

5.1. Fault hypothesis

The fault hypothesis considered is the following:

- **Node faults** – both masters and slaves are assumed to exhibit fail-silence failure semantics. This means that they can only fail by not issuing any message to the network. For the masters, this assumption is substantiated by their internal redundancy. For the slaves, this assumption can hold if internal redundancy is also used, or, if bus guardians are used instead, the assumption is restricted to timing faults.

- **Channel transient faults** – only transient faults that change the value of, at least, one bit are considered. Experimental data concerning CAN bit error rate [14] showed that CAN bit error rate in an aggressive environment can be as low as 2.6x10⁻³. Adapting the results of [15] to FTT-CAN, this value translates to at most 4 inconsistent message omissions per hour. Nevertheless, this work does not consider any particular constraint on the bit error rate nor on the duration of the error bursts but it is assumed that the resulting network inaccessibility periods will not go beyond the physical controllability limit of the system.

- **Channel permanent faults** – the transmission medium is a single point of failure of FTT-CAN and, thus, bus replication is mandatory to tolerate such faults. The bus replication mechanisms proposed in [17] are adopted, with the same message scheduling in the replicated buses. Notice that the possible bandwidth increase also proposed in [17] is not considered in this work.

- **Synchrony assumptions** – it is assumed that nodes, both masters and slaves, are always synchronized. This assumption is based on the fact that the trigger message transmitted by the active master, besides conveying the scheduling information, also acts as a synchronization mark to all network nodes. That is, the master node is also the time master and it is assumed that in between two consecutive trigger messages (typically 5 to 10 ms) the clock counters of each node do not diverge more than a negligible amount of time. In particular, bus guardians also have independent clock oscillators and synchronize on the reception of the trigger messages. As the synchronization requirements of FTT-CAN are relatively coarse, the assumption that masters and slaves are synchronized is assumed to hold even in the presence of error bursts that last for a relatively high number of consecutive ECs.

The reader should refer to [16] for further details on the fault hypothesis and on some underlying properties of CAN and FTT-CAN.

5.2. Modular architecture

The proposed architecture is based in FTT-CAN with replicated critical nodes and buses. Critical nodes are the ones implementing safety-related functions (x-by-wire) or the FTT-CAN master node. Non safety-critical nodes are not replicated but are also connected to two buses, to tolerate bus partition. The architecture also includes a gateway node that is necessary to configure the system at pre-run time. Once the system is running its parameters could be modified online, in a bounded, controlled and safe way, though requests issued to the master node by applications running in a slave node, as detailed in [18].

6. On going work

Currently, the VEIL is already functional despite using a subset of the proposed systems. At the moment only the accelerate-by-wire system and the dashboard are fully integrated in the proposed architecture. The accelerate-by-wire system is capable of generating positive and negative accelerations, thus causing an electrical braking effect. The energy generated during braking will later be recovered by the super capacitors, which are not yet deployed.
Both the steer and brake-by-wire systems are still under development. The respective functions are currently carried out mechanically. The batteries, DC-DC converter and solar panels are already installed but still operating autonomously. The whole system is expected to be fully functional in the near future, which will allow validating the proposed architecture under real operating conditions.

7. Conclusion

Small electrical vehicles present a set of interesting features, like a reduction on air pollution, increase mobility in urban areas, higher energy efficiency, higher economy, etc. On the other hand, the adoption of x-by-wire technologies brings sizeable benefits to the automotive systems, permitting important weight and cabling reduction, increased flexibility and maintainability and has the potential to permit a more efficient energy usage, with a noticeable impact on the operational costs and pollution reduction.

The paper proposes a modular distributed architecture with fault tolerant modes able to support x-by-wire functions, namely steer-by-wire, brake-by-wire and accelerate-by-wire, to be used in small electric vehicles. The FTT-CAN protocol is used as the communication infrastructure, serving both communication and task synchronization purposes.

The main contributions of the paper are the description of the vehicle architecture, the communication requirements and the discussion of the fault-tolerant architecture.

Table 1: Communication requirements

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<tbody>
<tr>
<td>1</td>
<td>pos_brk Brake position</td>
<td>1</td>
<td>10</td>
<td>f4</td>
<td>4</td>
<td>Pedal</td>
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<tr>
<td>2</td>
<td>pos_acc Accelerator position</td>
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<td>10</td>
<td>f4</td>
<td>4</td>
<td>Brake</td>
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<tr>
<td>3</td>
<td>vel_veil VEIL velocity</td>
<td>1</td>
<td>20</td>
<td>f4</td>
<td>1</td>
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</tr>
<tr>
<td>4</td>
<td>cur_im Motor current</td>
<td>2</td>
<td>20</td>
<td>f4</td>
<td>4</td>
<td>Solar panel</td>
</tr>
<tr>
<td>5</td>
<td>vel_im Motor velocity</td>
<td>2</td>
<td>20</td>
<td>f4</td>
<td>1</td>
<td>Road wheel</td>
</tr>
<tr>
<td>6</td>
<td>tmp_vfd VFD temperature</td>
<td>1</td>
<td>1000</td>
<td>f4</td>
<td>1</td>
<td>Batteries</td>
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<tr>
<td>7</td>
<td>vol_dch High voltage DC-link voltage</td>
<td>2</td>
<td>20</td>
<td>f4</td>
<td>2</td>
<td>Super capacitor</td>
</tr>
<tr>
<td>8</td>
<td>eng_sp Solar panel energy</td>
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<td>1000</td>
<td>f4</td>
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<td>ang_stw Steering wheel angle</td>
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<td>10</td>
<td>f4</td>
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<td>General board</td>
</tr>
<tr>
<td>10</td>
<td>ang_whl Wheel angle (direction)</td>
<td>2</td>
<td>10</td>
<td>f4</td>
<td>2</td>
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<tr>
<td>11</td>
<td>eng_bat Batteries energy</td>
<td>2</td>
<td>500</td>
<td>f4</td>
<td>2</td>
<td>General board</td>
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<tr>
<td>12</td>
<td>tmp_bat Batteries temperature</td>
<td>1</td>
<td>1000</td>
<td>f4</td>
<td>1</td>
<td>General board</td>
</tr>
<tr>
<td>13</td>
<td>pwr System power</td>
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<td>250</td>
<td>f4</td>
<td>3</td>
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<td>14</td>
<td>sos Emergency button</td>
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<td>-</td>
<td>-</td>
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<td>15</td>
<td>aes Auxiliary electrical signals</td>
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<td>100</td>
<td>f4</td>
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<td>eng_sc Super capacitor energy</td>
<td>2</td>
<td>50</td>
<td>f4</td>
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<tr>
<td>17</td>
<td>vol_dcl Low voltage DC-link voltage</td>
<td>2</td>
<td>100</td>
<td>f4</td>
<td>4</td>
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</tr>
<tr>
<td>18</td>
<td>cur_dcl Low voltage DC-link current</td>
<td>2</td>
<td>100</td>
<td>f4</td>
<td>2</td>
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<td>f4</td>
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<td>1</td>
<td>500</td>
<td>f4</td>
<td>2</td>
<td>General board</td>
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</tbody>
</table>

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