Design approaches for integrating CAN with emerging time-triggered protocols

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Time triggered network technologies are now entering into automotive electronic architecture designs. At the same time the number of ECUs integrated within a vehicle is growing, mostly integrated using CAN technology. Control applications on the next generation of vehicles will utilise LIN, CAN and FlexRay network technologies. A signal representing a real world physical quantity such as engine speed may traverse across several of these different networks. This paper investigates future requirements for the design of a vehicle's electrical architecture. Particular attention is given to the mapping of CAN to time triggered protocols for efficient gateway design, Object Oriented Design and the XML expression of a vehicle electronic control system, and the optimisation of the electronics architecture in terms of cost and network utilisation.

1 Introduction

The Controller Area Network (CAN) and Local Interconnect Network (LIN) are now common networking technologies used within modern automotive electrical control architectures. FlexRay is an emerging technology that has recently been implemented in a BMW passenger car, and there is the likelihood that other networking technologies will appear in future vehicle electrical architectures to enable the integration of an increasing number of electronic control systems. Research is underway at the University of Warwick sponsored by the UK's Engineering and Physical Sciences Research Council and Rapicore Limited, concerning how to holistically design a vehicle's electronic control architecture. A current key problem is that there are technology dependent methodologies used for design of the individual networks in a distributed electronic architecture. They exist as islands of technology that have grown from different consortia or companies. A holistic solution is needed that can be used to integrate each of the different network technologies and design processes, and also provide optimisation of the costing of the vehicle electrical architecture.

The aim of the work described in this paper is to highlight the key issues involved with vehicle electronic architecture design for real-time control systems which scope includes CAN, LIN, TTCAN and FlexRay control networks. In particular the following sections cover the issues involved from a network protocol technology and in-vehicle networking design process view point. Both advantages and disadvantages that Object Oriented Design (OOD) can bring to a potential holistic design process are highlighted. Finally potential solutions that can bring forward a holistic vehicle electrical architecture design process are discussed.

2 Automotive in-vehicle control network comparison

The requirements of electrical architecture differs across passenger car, bus & truck and off-highway automotive industries (Axelsson et al, 2003). These differences influence the number of networks and the types of network technologies used.

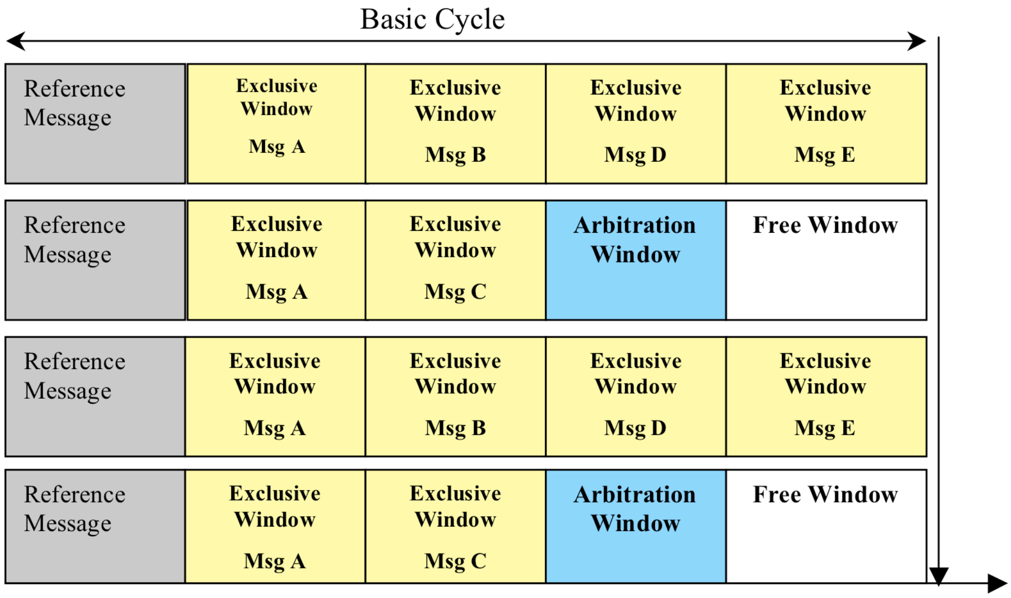

Figure 1: An example of the Communication Matrix of a Time Triggered Network communication (in this case TTCAN)

2.1 Controller Area Network (CAN)

CAN was developed by Robert Bosch GmbH in the 1990s (CAN Specification Version 2.0; 1991) and has become the most prominent open standard network protocol across the world's automotive industry. The Controller Area Network is standardised under ISO-11898. The main characteristics of CAN are event based communication, 11 or 29 bit identifiers, bus access is CSMA/CD with Non-Destructive Bitwise Arbitration, and re-transmission of messages that lose arbitration.

2.2 Time Triggered CAN (TTCAN)

The CAN standard ISO11898 has been extended under ISO-11898 part 4 to Time Triggered CAN (TTCAN) to address the determinism problems of CAN and therefore make it more applicable to safety critical applications. The main characteristics of TTCAN is that bus access is controlled via a Time Division Multiplexed Access (TDMA) like method using a regularly repeating cycle of time called the *Basic Cycle* (see figure 1). The *Basic Cycle* is divided into a fixed number of time windows (i.e. fixed at design time) which can be a mixture of any one of four types; *Reference Message*, *Exclusive Window*, *Arbitration Window* and *Free Window*. This is sent by the time master control unit (global time master) and controls the timing of the Basic Cycle (Hartwich et al, 2000). It is currently available for commercial exploitation using automotive qualified silicon, effectively doubling the usable bandwidth of CAN (Pope et al; 2005). However, there are to date no commercial automotive applications.

2.3 Local Interconnect Network (LIN)

The Local Interconnect Network has been proposed for intelligent automotive sensor and actuator applications such as switches and motors (Wense; 2000). Revisions 1.2 and 1.3 are implemented in some vehicles and v2.0 has been developed to allow enhanced diagnostics and pseudo-plug and play sensor applications. LIN is a simple protocol whose specification has been aimed at low-end microcontrollers that have a USART peripheral. Many body control functions are often simple digital on/off operations such as activating lights, wipers, windows etc. These are considered soft requirement real time systems that do not necessarily need the level of response that can be provided by CAN. Such systems are typically integrated into the vehicle electronic architecture via a LIN to CAN gateway.

The main features of LIN are that it is limited to 20Kbaud and allows transfer of up to 8 bytes of information at a time. A deviation from the LIN consortium's main LIN protocol is SAE J2602 which is a variant of LIN 2.0 and is fixed to 10.4 Kbaud for compatability with the legacy SAE J1850 protocol used by US manufacturers.

2.4 Flex ray

TTP/C (Time Triggered Protocol for Class C networks) and Byteflight were the first networking technologies proposed to satisfy the requirements of a future high speed control network with safety features suitable for drive-by-wire. These were proprietary technologies and therefore work on an open industry standard commenced. FlexRay development commenced in 1999 as an alternative to TTP/C and Byteflight technologies, and as a step change in the data throughput provided by CAN. The FlexRay consortium was launched in the year 2000 to develop the FlexRay specifications and market. It consisted of core members BMW, DaimlerChrysler, FreeScale (previously called Motorola), Philips Semiconductors, Robert Bosch and Decomsys. The FlexRay concept was introduced in 2001 (Berwanger at al, 2001). The aim of FlexRay is to complement CAN in higher bandwidth and integrity applications and is now at revision 2.1. This has a maximum network bit rate of 10Mbit/s. Since CAN is typically not used at a rate above 500 Kbit/s, FlexRay therefore provides up to 20 times more data throughput per channel. FlexRay also utilises the concept of a Communication Matrix in a similar way to that used in TTCAN and shown in figure 1.

2.5 Network technology discussion

Table 1 compares each of the network technologies described in this section. It can be seen that all of the protocols except CAN have some mode of deterministic operation specified in the protocol by being TDMA.

3 In-vehicle network design processes comparison

3.1 Non-deterministic approach

The design of in-vehicle networked based systems has evolved over the last twenty years. Originally, early protocols such as J1850, Seriplex, VAN and CAN were developed under a process in which the message transmission from ECUs was designed with little regard to the underlying bus technology characteristics. In the case of CAN, the protocol itself was relied upon to schedule the message transmission effectively.

For most of the 1990s, this type of process was followed by most vehicle manufacturers for the development of CAN based systems. It is still followed to some degree by many for CAN based systems even today. However, it created a number of problems during systems integration such as non-deterministic message delays and bus loading. It is a well known feature of CSMA-CD (Carrier Sense, Multiple Access, Collision Detection) type networks such as CAN that they can operate with reasonably predictable message latency up to about 40% bus loading. An excursion beyond this leads to great variability in the latency for lower priority messages.

3.2 Pseudo-deterministic approach

	CAN	TTCAN	FlexRay	LIN
Network Access Methodology	Event	TDMA	TDMA	TDMA
Message Latency	Variable	Deterministic for Exclusive windows. Variable for Arbitration windows	Deterministic for Static Slot. Variable for Dynamic Slot	Deterministic for Unconditional frames only, variable otherwise

Table 1: Comparison of major automotive network protocols and network access

A solution to the bus loading problem of the Non-Deterministic approach was developed in Volvo (Tindell, 1994) that could determine the worst case message latency by assigning higher priority (or periodicity) signals to higher priority CAN messages. Lower priority (or periodicity signals such as those that are event triggered) signals are assigned to lower priority CAN messages. The result of this was that the CAN bus was able to run at a higher loading, with the worst case latency known at design time of CAN messages and therefore design tradeoffs were able to be made to ensure acceptable latency.

This is a Pseudo-Deterministic Approach since the determinism is defined as a worst case latency and is the process that has been implemented in the Volcano tools (Rajnak and Ramnefors; 2002). The key principles of this CAN design process are based on a Publisher-Subscriber model (Navet et al; 2005). This methodology improves the procedure of traditional CAN bus development using a Non-Deterministic methodology, since it allows the OEM to deal much better with multiple system suppliers.

3.3 Deterministic approach

Pseudo-Deterministic Approaches for CAN and work by Kopetz on the Time Triggered Protocol (TTP) (Kopetz and Thurner, 1998) has led the way to the improved Deterministic Approach to design for time triggered protocols. Time triggered protocols are deterministic in their nature and their associated design process deals with the systems integration issues much better as they allow the designer to easily conceptualise the communications timing and map signals and messages across different buses. They are also good for dealing with the problem of multiple suppliers in the same way as Pseudo-Deterministic approaches.

3.4 In-vehicle network design process discussion

A comparison of Non-Deterministic, Pseudo-Deterministic and Deterministic in-vehicle network design processes is shown in table 2. Pseudo Deterministic and Deterministic approaches allow the systems from the Suppliers and the OEMs to be integrated easier. The final result of the approaches is a communications schedule that should not show problems during system integration and vehicle testing that are caused by message or signal latency problems.

A significant problem with Time Triggered design approaches is that time triggered protocols such as LIN and FlexRay buses need to interface with the CAN protocol since it is the most commonly used for powertrain, chassis and body control. Since CAN is a less deterministic protocol when compared to time triggered protocols, the design of a gateway between CAN to either LIN or FlexRay is not so straightforward. A solution can be to visualise the CAN communication also as a communication matrix in a similar way as with the time triggered protocols.

	Non-Deterministic	Pseudo-Deterministic	Deterministic
Industry Standardardisation	Proprietary, not industry standard	Proprietary, not industry standard	Proprietary, not industry standard
Network Conceptual Owner	Conceptually no one company owns the network, it is simply a communication medium	Network owner is vehicle OEM	Network owner is vehicle OEM (except in the case of LIN, it might be a 1st tier supplier e.g. seats).
Approach Openess	Yes	Proprietary Vendors	Proprietary Vendors
Schedule Design	Messages and signals assigned by OEMs and suppliers together, the CAN protocol itself is left to sort out the scheduling of transmission. Bus loading kept conservatively low to ensure that message latency problems are not significant.	OEM design signals and their periodicity with the advice of suppliers. Signals are assigned to messages, automatically by a software tool. Suppliers receive network specification and/or software kernel from OEM, which includes description of messages, schedule, signal assignment to messages	OEM design signals & their periodicity with the advice of suppliers. Signals are assigned to messages, manually and automatically by a design tool. They are assigned to messages with the appropriate periodicity. Supplier's ECU signals and messages are precisely assigned to specific slots of the communication schedule.
Problems	Bus loading and inefficiency Proprietary solution	Limited to CAN Proprietary solution	Does not integrate CAN Proprietary solution

Table 2: Comparison of automotive network design methodologies

4 Object oriented design (OOD)

Object Oriented Design processes are now starting to be used for the design of automotive electrical architectures. It has been noted that OOD methods have been slow to be adopted within the automotive industry (Axelsson, 1999), possibly due to it not being well understood or seen as appropriate to real-time systems. Reduced silicon costs (e.g. esp. ROM/RAM) and the emergence of better OOD tools utilising the Unified Modelling Language (UML), now mean that significant adoption is taking place. AUTOSAR (Automotive Open System Architecture) is a consortium responsible for the design of embedded software components that abstract the application software away from the microcontroller and ECU hardware. The specifications of AUTOSAR are currently being developed with OOD very much in mind.

One system safety design project (Johannessen and Torin; 2003), proposed a design process for drive-by-wire systems which had the following system partitioning procedure, regardless of network technology used:

- Functional failure analysis leads to system safety requirements
- Network nodes are added at locations of sensors and actuators. This leads to the design of a non-redundant architecture
- Finally the appropriate redundancy is added.

This approach to design is logical, but would currently only commercially work for an enclosed system (e.g. steer-by-wire). Currently network nodes are not necessarily placed at the location of sensors and actuators. For practical reasons of cost and packaging, the more typical situation is to have a centralised control ECU for a system (e.g. ABS system will have one ECU with one wheel speed sensor located at each of the wheels).

5 Discussion of potential solutions

The previous sections have discussed automotive networking technologies and design processes that are used for the integration of automotive electronic systems using such technologies. Issues with automotive networks and their design process have been highlighted. This section will discuss some possible solutions to some of the issues raised.

5.1 Data visualisation and mapping between network technologies

The time triggered design process works by visualising the message schedule as a Communication Matrix of *n* columns (called Windows or Slots) by *m* rows (or Cycles). This way it makes it easy to conceptualise the timings of the different messages and work out how they can be mapped between different networks and network types. TTCAN and FlexRay are already represented in terms of such a Communication Matrix. However, LIN and CAN protocols are not naturally designed or visualised in this way. Figure 2 shows the concept of a LIN Communication Matrix as introduced in the LIN-Plan tool produced by TTTech AG, and how it is unravelled to the traditional LIN schedule that is contained within the LIN specifications. Use of this method allows LIN to fit better into the TT design process.

CAN is not a deterministic protocol in the same sense as protocols such as LIN, TTCAN and FlexRay. The latency for a particular CAN message transmission is non-deterministic since its latency is dependent upon the other messages that could be transmitted on the CAN bus. However, methods by Tindell (Tindell et al, 1994) can calculate the worst case latency of CAN message transfer. Therefore this may be used to map CAN data for transfer to LIN or FlexRay. Providing that the maximum possible message transfer time is less than the message period, then the bus is not overloaded and the message will not miss its deadline.

5.2 Data encapsulation of signals and data exchange formats

Data encapsulation is a feature of Object Oriented Design that categorises data into Private, Public and Protected, which determines whether they are available to all classes, sub-classes or only the defining class. In the context of vehicle electronic system design, the requirement is that the class could represent an ECU or a network / sub-bus. Therefore it may be desirable to have a network signal within a LIN seat (e.g. motor current) as Private data since it is not required outside of the seat cluster. However, another network signal originating within the same cluster may be required outside LIN seat (e.g. seat position) and provided externally of the LIN seat via a LIN to CAN gateway. Therefore such a signal would be Public data.

There are now a number of file formats for data exchange that support the description of network data from the vehicle platform down to the signals representing physical quantities such as motor current and seat position. However some of these are more able for the purpose than others. CANdb / CANdb++ are proprietary file formats that have become accepted as de-facto standards and are examples of file format that allow numerous signals to have the same name and be assigned to different messages, even if the signal properties are different. This can create confusion if these signals are not representing the same physical property. The LIN Description File (LDF) (LIN Consortium, 2003) is an example of a file format that only allows unique naming of signals and is an improved approach. A signal is Published By or Subscribed By a LIN Node, and its properties (e.g. Length, Scaling, Offset, Units) remain consistent throughout the LIN network. A signal is referenced by a message, start bit within the message is therefore the property of the message and not the signal. However, LDF has been designed for data exchange on a single LIN network and is therefore not appropriate for the purpose of exchange of multiple LIN network data or onto other network protocols. Only the forthcoming AUTOSAR and ASAM driven FIBEX methodologies (ASAM; 2005) suit the final requirements of Object Oriented Design, however a full comparison of the capabilities of the two has not been published to the authors' knowledge. AUTOSAR is aimed at describing the ECU internally and the vehicle architecture, whereas FIBEX is focused on in-vehicle network data exchange. However FIBEX is very good at stating consistent terminology for the description of components in a distributed automotive electronic control system.

From an Object Oriented Design viewpoint, a Public signal generated from a sensor on a LIN bus, should keep the same name if it is transferred via a gateway to CAN and FlexRay. A signal should have the same name across all networks and I/O ports if it represents the same physical quantity and therefore its scaling has not changed.

5.3 Costing and models

The use of in-vehicle networking reduces use of redundant sensors. The wiring harness is one of the most expensive components in a modern vehicle after the engine. FlexRay implementation leads to increased nodal cost. Nodal costs are a function of software stack and hardware features. The software stack impacts costs via ROM, RAM and CPU utilisation. These properties are each a function of the number of Signals, Messages, Schedules and Network Nodes. The hardware impacts costs via choice of physical layer, oscillator and power regulator. The BMW X5 is the first production car to implement FlexRay. Although the nodal costs of FlexRay are higher, an interesting reason for choosing FlexRay, is that it can replace several CAN buses thus reducing wiring, connectors, gateways and reduce system partitioning effort (Berwanger et al; 2005). The vehicle electronic system architecture and its costing is extremely complicated and is a function of component features such as connector size, wiring harness size and routing, ECU costing (including embedded software costs), sensor costing, system redundancy provision and development tool costs.

LIN Matrix

Message A	Message B	Message D	Message E
Message A	Message C	Message D	Free
Message A	Message B	Message D	Free
Message A	Message C	Message D	Free

Unravelled LIN Matrix

A	B	D	E	A	C	D		A	B	D		A	C	D	

Resultant LIN Schedule

A	B	D	E	A	C	D	A	B	D	A	C	D

Figure 2: LIN Matrix Based Design and the Resultant LIN Schedule, i.e. Message D has a delay time twice that of the other messages, since it is followed by a free window. The Result LIN Schedule conforms to the LIN specifications

6 Conclusion

A holistic signals oriented design process which can support the needs of both time-triggered (e.g. LIN and FlexRay) and non-time time triggered protocols (e.g. CAN) is needed. Object Oriented Design is a good approach for designing at an architectural rather than bus level. It is an approach that is compatible with AUTOSAR based embedded software designs. AUTOSAR itself will allow easier changing of embedded software component suppliers and network protocols used by ECU suppliers. Although AUTOSAR does provide definition of network protocol embedded software components, there are a number of related issues that require a solution, and therefore improve the vehicle electrical design process.

The CAN protocol does not fit easily into the Time Triggered design process but proposals have been made that suggest it is better to visualise as a communication matrix and therefore aid the signal/message mapping process. Visualising and designing CAN in this way means that it matters less whether a network is designed as CAN or TTCAN. TTCAN fits into the time triggered design process better and may eventually see some adoption in the future. If CAN is to be visualised in this way, research is required to ensure that this methodology is effective.

File formats such as CANdb/++ and LDF are not capable for the future descriptive requirements of the vehicle electronic architecture and allowing effective data exchange. Two new emerging XML based file formats are being proposed by the AUTOSAR and ASAM consortiums and satisfy the requirements of Object Oriented Design. A comparison of the capability of the two formats is to be carried out.

The choice of the appropriate architecture and use of number of networks is a very complex design problem when considering optimising real-time performance, system safety and cost. CAN is a very common, well understood technology and is suitable for most automotive real-time control applications. However, LIN provides the opportunity to improve integration of intelligent sensors and actuators, whilst further reducing cost. Additionally, the emerging FlexRay protocol is more expensive to implement in terms of its nodal costs, but its significantly larger bandwidth compared with CAN, means it can replace numerous CAN buses and leave a lot of bandwidth free for future expansion. This potentially cuts costs by reducing the need for connectors, wiring, and additional nodes, such as gateways.

The mapping of CAN into a pseudo- Time Triggered Communication Matrix for efficient gateway design, representation of the entire vehicle electronic control system in XML and architecture cost optimisation is the subject of current research.

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