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Message scheduling with reduced matrix cycle and evenly distributed sparse allocation for time-triggered CAN

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ABSTRACT

Controller Area Network (CAN) was initially developed as an in-vehicle real-time communication bus. Due to its low cost and high reliability, it has also become a widely accepted standard in industrial distributed control applications. The CAN protocol has an event-triggered architecture. Although its priority based medium access mechanism provides guaranteed immediate access for the highest priority messages, it may cause unpredictability in communication media for the lower priority messages. In order to address the problems caused by the event-triggered architecture, different time-triggered network architectures, such as TTP, Byteflight, and Flexray, have been introduced.

This paper focuses on time-triggered CAN (TTCAN), which is built on the existing CAN standard with the addition of time division multiple access (TDMA). In order to combine the advantages of the event-triggered and time-triggered communication to meet the requirements of the distributed real-time systems, it is crucial to construct feasible message schedules. In this study, a schedule construction method, based on the reduced matrix cycle and evenly distributed sparse allocation, is introduced to produce the best optimum message schedules possible in terms of the message delay performance. The simulation results show that the method introduced in this study provides significant performance improvement not only for the time-triggered messages but also for the event-triggered messages.

1. Introduction

Modern upper class vehicles may have up to 70 electronic control units (ECU) exchanging up to 2500 signals using in-vehicle communication networks (Albert, 2004). Controller Area Network (CAN) is a widely accepted real-time communication bus for in-vehicle applications. CAN provides a robust communication environment for ECUs, comprised of microcontrollers, sensors, and actuators.

Real-time networks provide communication for both sporadic and periodic messages with deadlines, which describe the latest transmission time. The CAN protocol employs a mechanism called Carrier Sense Multiple Access with Collision Detection (CSMA/CD) with non-destructive bit-wise arbitration as the medium access method (Lawrenz, 1997; CAN Specification, 1991). Although this mechanism provides a guaranteed response time for the highest priority message, there is no guaranteed upper bound for delays encountered by the lower priority messages, especially under the high bus-load and fault conditions. However, it is an important issue to meet deadlines in safety-critical hard real-time applications, such as X-by-wire systems, which require deterministic behavior and high performance. As the arbitration mechanism of the event-triggered CAN does not meet these requirements, the time-triggered CAN (TTCAN) concept has been developed (Leen and Heffernan, 2002). Several other time-triggered networks (Gena et al., 2005; Paret, 2007) such as time-triggered protocol (TTP) (Kopetz and Bauer, 2003), Byteflight (Byteflight Specifications), and Flexray (FlexRay Specifications) have also been introduced. This paper focuses on TTCAN, which provides a deterministic behavior by imposing a TDMA structure over the existing CAN standard. TTCAN has been standardized and described in ISO 11898-4 (2004).

According to the medium access method applied, the real-time networks can be classified as event-triggered and time-triggered. Hybrid networks also constitute another class combining features of both types. In the event-triggered networks, messages are produced according to the occurrence of events and the medium access is provided in a dynamic way for messages. In the time-triggered networks, messages are produced at regular time intervals and the medium access is arranged in pre-defined time-windows in a TDMA manner.

The time-triggered systems have the advantage of deterministic behavior, whereas the event-triggered systems have the ability to react fast to asynchronous external events (Albert and Hugel, 2005; Albert and Gerth, 2003). As a hybrid system, TTCAN is expected to combine the features of both systems. Real-time

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performance of a time-triggered system depends on the scheduling of the messages in the system matrix (SM). Producing system matrices with high performances, especially for event-triggered messages, raises the problem of message scheduling.

This paper introduces a method to establish system matrices to achieve optimal performance results in terms of message delays for both time-triggered and event-triggered messages. In Section 2, information about the fundamentals of CAN and TTCAN is presented, and some previous work about the message scheduling is summarized. In Section 3, the proposed message scheduling algorithm and its application with the SAE benchmark are explained. Section 4 presents information about the modeling and simulation of the proposed system. In Section 5, the performance of the proposed system is evaluated according to the simulation results. Conclusions and final remarks are given in Section 6.

2. CAN, TTCAN, and message scheduling

2.1. CAN protocol

CAN is an event-triggered network, which provides communication for real-time messages with a bus speed up to 1 Mbps. Each message in CAN has a unique identifier, which also determines the priority of the related message. The standard CAN 2.0A frame has an 11-bit identifier field. The medium access control method is based on the priority of the identifier where the logic bit state "0" has priority over the bit state "1".

Bit-levels are represented by non-return-to-zero (NRZ) encoding, and in order to maintain synchronization among nodes, bit stuffing is realized after every 5 consecutive same bit level occurrence. Therefore, the longest time (C_m) taken to send a message m on the bus can be calculated as (Tindel and Burns, 1994; Navet et al., 2000)

$$c_m = \left(\left\lfloor \frac{34+8S_m}{4} \right\rfloor + 47 + 8S_m \right) \times T_{bit} \quad (1)$$

where S_m is the size of data field in bytes. The size of the fixed fields of a CAN frame is 47 and 34 bits of them are subject to bit stuffing. As the standard CAN frame may contain 0 to 8 data bytes, the maximum size of a stuffed CAN frame may be in the range 55–135 bits. T_{bit} is the bit-time of the bus, for example it is 1 μs at 1 Mbps bus communication speed. Fig. 1 shows the structure of the standard CAN 2.0A data frame.

CAN has a multi-master structure, and in the CSMA/CD with non-destructive bit-wise arbitration method, any node can start transmission if the bus is idle. If two or more nodes try to transmit messages at the same time, bit-wise arbitration mechanism resolves the conflict and the message with the highest priority is transmitted first. The 11-bit identifier field determines the priority of the message. The message with the binary value closest to zero has the highest priority. When a high priority message wins the arbitration and gets the bus access, the lower priority messages must wait for the bus to become idle. Hence, the worst-case message response time R_m of a given message, defined as the longest time between the start of a task queuing message m and the latest time that the message arrives at the destination station, can be given as (Tindell and Burns, 1994; Navet et al., 2000)

$$R_m = J_m + W_m + C_m \quad (2)$$

where J_m is the queuing jitter of message m, which gives the latest queuing time of the message relative to the start of the sending task on the host CPU. W_m is the queuing delay of message m caused by higher priority messages and a lower priority message that has already obtained the bus.

From these explanations, it can be seen that although the highest priority message is granted immediate bus access in event-triggered CAN, the lower priority messages may face extensive bus access delays. In order to find a solution for the nondeterministic behavior of the CAN protocol, the TTCAN concept, which provides a deterministic feature, has been developed.

2.2. TTCAN concept

The TTCAN standard corresponds to the Session Layer of the Open System Interconnection (OSI) reference model. Whereas, the CAN standard corresponds to the lowest two layers of the OSI reference model: the Physical Layer and the Data Link Layer. TTCAN imposes a TDMA architecture over the existing event-triggered CAN protocol. Fig. 2 shows CAN and TTCAN with the corresponding OSI reference model layers. In this architecture, synchronous timing is implemented at each network node in order to obtain time-triggered behavior. A common global time is used to synchronize all nodes by a periodically transmitted reference message. In TTCAN, each node holds a replica of global time in the form of a counter, and its value is incremented once every network time unit (NTU) (Leen and Heffernan, 2002).

In TTCAN, time synchronization is defined in two levels: Level 1 and Level 2. Level 1 realizes synchronization necessary for the time-triggered message scheduling. Level 2 is an extension of Level 1, and has a high precision global time base related to the physical second. This level allows TTCAN to synchronize and interface to other networks (Leen and Heffernan, 2002). Reference messages are composed of 1 byte and 4 bytes for Level 1 and Level 2, respectively.

As in TDMA, messages are exchanged within a fixed sequence of time windows. The complete transaction sequence organized as the matrix cycle (MC), also known as the SM, is repeated

Application Layer	
Presentation Layer	
Session Layer	TTCAN Session Layer
Transport Layer	
Network Layer	
Data Link Layer	CAN Layers
Physical Layer	

Fig. 2. OSI reference model with corresponding CAN and TTCAN layers.

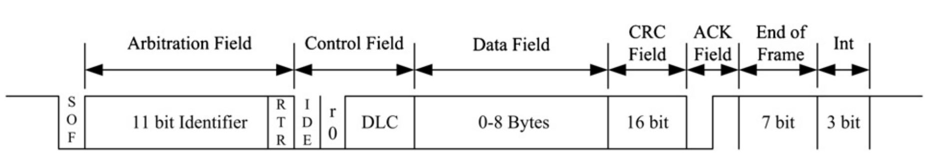

Fig. 1. Standard CAN 2.0A data frame format.