Migration from CAN to TTCAN for a Distributed Control System

A. Albert, R. Strasser, A. Trächtler

Besides the well established event triggered bus protocols (such as, for instance, the CAN bus protocol) recently the demand for time triggered communication systems has intensified. In order to accommodate demand, an extension of the CAN bus protocol to TTCAN (Time Triggered CAN) has been specified in ISO 11898-4. In the meantime also a silicon implementation of TTCAN is available.

Since there are no TTCAN compliant sensors and ECUs so far, for an initial examination an intelligent CAN/TTCAN gateway has been developed. In this way a laboratory style migration of a distributed control system which actually was developed around the CAN bus to its time triggered version TTCAN easily succeed. This migration is carried out here exemplarily by means of a vehicle dynamics control concept. Furthermore, the article gives some remarks concerning the synchronization of the sensors and the task management with the bus cycle.

1 Introduction

In recent years the amount of electronic devices in automobiles has drastically increased. This applies to the number of sensors, actuators and electronic control units (ECU) as well as the number of electronic devices for entertainment and navigation systems. In order to efficiently handle the large amount of data, bus systems are used. Thereby a compromise must be found between economical aspects on the one hand and technological considerations on the other hand – for instance resulting from the data rate and the required safety concept. A comprehensive overview addressing the different bus concepts in the automotive field can be found in [Ran02].

For chassis control systems and power train communication the event triggered CAN bus [CAN90] has established itself as a de facto standard. Since modern control concepts, such as X-by-wire require highly dependable architectures, recently the demand for time triggered communication systems has intensified. For the mentioned applications time triggered concepts are expected to be superior compared to event triggered concepts, since their behavior is quasi deterministic during regular operation. Usually time slices define the permission to access the bus (time division multiple access, TDMA) such that the timeliness of all messages can be guaranteed [Kop97]. An other very interesting property from the point of view of the automotive field is the so called composability. Since the time slices to access the bus are predefined, the behavior along the time axis is decoupled from the actual bus load. In fact, the predefined phases among the messages are constant. Thus, it is possible to develop different subsystems independently (e.g. by the car manufacturers and suppliers) and subsequently to merge them into the complete system. There are of course also some disadvantages in comparison with event triggered systems. For example, event triggered systems have a better real-time performance when reacting to asynchronous external events which are not known in advance [AG03]. Another advantage is their higher flexibility. Thus, some busses try to merge the advantages of both concepts (event and time triggered) as for instance TTCAN [LH02, MFH$^+$02] or FlexRay [BBE$^+$02]. It is not within the scope of this paper to intensively compare the different properties of event and time triggered systems. Works which address such a comparison are, for instance, [Kop00, APF02].

As already mentioned the CAN bus became very popular in automotive applications. In order to accommodate demand for time

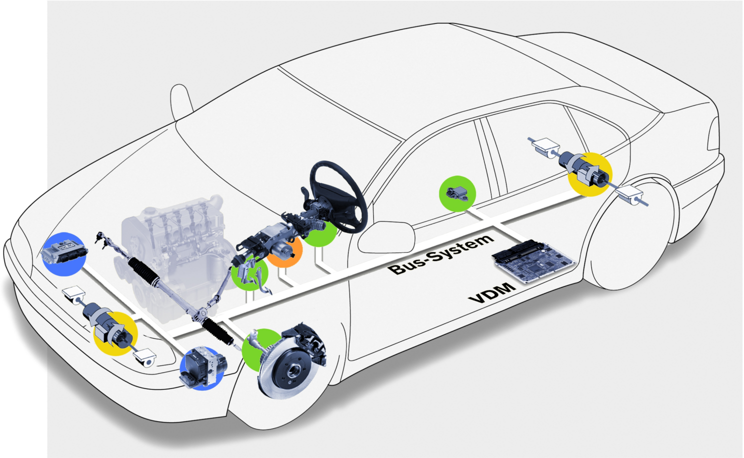

Figure 1: Vehicle Dynamics Management with the components ESP (**E**lectronic **S**tability **P**rogram) (intervention mainly via the brakes), AFS (**A**ctive **F**ront **S**teering) (intervention via the steering angle), EAR (**E**lectronic **A**ctive **R**oll Stabilizer), (intervention via the stabilizers)

triggered architectures, an extension of the CAN bus protocol to TTCAN (Time Triggered CAN) has been specified by the International Standardization Organization in ISO 11898-4 [Org]. In the meantime also silicon implementations are available, e.g. from Bosch [Har02] or Infineon [LKK03].
On the base level the TTCAN communication is still carried out with the physical CAN bus. Hardware components on this level are proved and tested in millions of applications. Thus, all experience with the development of CAN based systems can still be utilized. Since further the TTCAN specification allows a free scalability between time triggered and event triggered operation, the migration to time triggered communication is simplified.

Within the current study a time triggered architecture should be investigated for a distributed control system. The Bosch global vehicle dynamics control concept, namely the Vehicle Dynamics Management (VDM) [TL02] is envisaged as an example application. The idea of the VDM is to merge different control systems in order to simultaneously increase the safety, the stability and the comfort of the driving. An efficient implementation implies a safe and adequate communication between the participating ECUs and sensors. Currently, the communication is accomplished with a more or less slack coupling via CAN. Within the study a migration to TTCAN is carried out in order to investigate the fundamental aspects of time triggered architectures like the necessary synchronization between the bus and the ECUs on the one hand and the bus and the sensors on the other hand.
This paper is organized as follows:
Section 2 shortly describes the architecture of the Vehicle Dynamics Management VDM. Further, the current communication structure on the basis of CAN is sketched and the desired concept of the study based on TTCAN is presented. Since there are neither ECUs nor sensors currently available which support TTCAN, a CAN-TTCAN-Gateway has been developed. Section 3 describes the realized printed circuit board (PCB). Besides the hardware description, the utilization of the gateway is shown in order to realize the migration from CAN to TTCAN. Furthermore, the time behavior (performance) of the gateway is presented. As already mentioned, for an efficient implementation of the time triggered architecture it is necessary to synchronize the bus with all participating nodes, the ECUs as well as the sensors. Subsection 3.4 demonstrates the synchronization of the yaw rate sensor with the TTCAN bus. The paper ends with a summary in section 4.

2 Vehicle Dynamics Management

Figure 1 illustrates the concept of the Vehicle Dynamics Management. The VDM is an approach for coordinating vehicle dynamics functions by control of active chassis systems. This superior control strategy combines several control concepts and prevents negative interference without restricting the functional range. Thus, simultaneously the safety, the stability and the comfort of the driving is increased. Currently, three control systems are integrated in the VDM: active braking, active steering and active suspension.

- The **E**lectronic **S**tability **P**rogram (ESP) actively stabilizes the motion mainly via the modulation of the brake pressures. The system is able to systematically generate yaw torques in order to influence the lateral dynamics [Zan02]. Particularly, the intention of the ESP is to prevent extreme understeering and oversteering when the car turns too fast or on slippery surfaces. Important sensors are the yaw rate sensor (YR), which measures the yaw rate and the lateral acceleration of the vehicle and the steering-wheel angle sensor (SA), which measures the steering angle and its time derivative.
- The **A**ctive **F**ront **S**teering (AFS) is capable to vary the actual steering angle by an overriding drive which adds an electronically generated steering angle to the driver's steering input [KLS99]. Besides the possibility to actively increase the stability (mainly of the lateral dynamics) it is possible to vary the actual steering angle in relation to the steering command from the driver and other factors. Thus, not only safety but also comfort and driving pleasure is addressed by this system.

- The main purpose of the **E**lectronic **A**ctive **R**oll Stabilizer (EAR) is to suppress rolling during cornering of the vehicle [KLV99]. For that purpose active stabilizers are introduced which are able to shift the forces between the wheels of each axis.

The discrete systems partially act on different dynamics of the system; however, there are also dependencies which have to be taken into account. Generally, different control concepts can cooperate, compete or merely coexist. The former two (ESP and AFS) require an adequate exchange of data (communication) in order to assure an efficient operation. Thus, networking is of essential importance.

Figure 2 shows the actual architecture of a lab car with a combination of ESP with AFS.

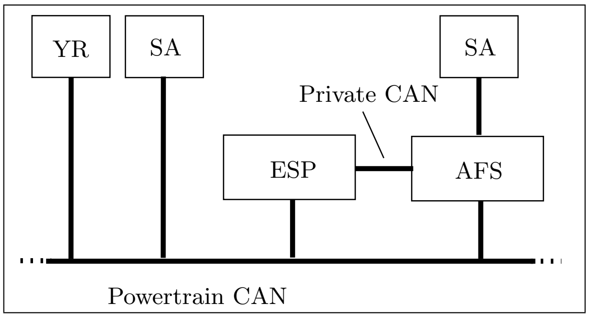

Figure 2: VDM lab car with ESP and AFS

Some sensor data are required by both systems, the ESP and the AFS. Such data are for instance the wheel speeds which are available from the Powertrain CAN. The yaw rate sensor (YR) and the steering angle sensor (SA) also communicate via this bus. Another steering angle sensor is connected to the AFS and transmits the real steering angle (driver's desired steering angle plus additional angle of the AFS). Further, there are crucial data between the ESP and the AFS which are exchanged via a private CAN communication.

Figure 3 illustrates two alternative architectures for the study. For alternative a) all sensors communicate via the so called chassis bus, which in this case should be imple-

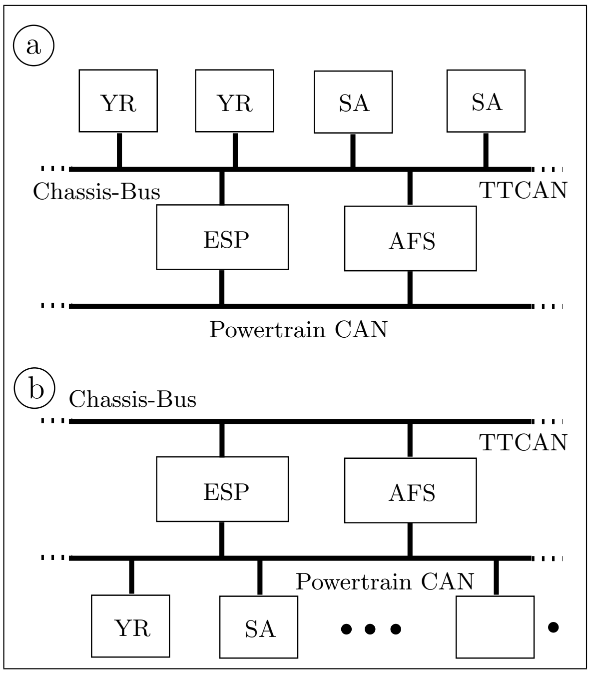

Figure 3: Two envisaged architectures for the case study of the VDM

mented as a TTCAN bus. For alternative b) the chassis bus connects all participating ECUs whereas the sensors are connected to the powertrain CAN. It is emphasized that both architectures merely present laboratory studies. In order to realize a time triggered communication with as much as possible participants in the following alternative a) is preferred. The goals of the study are

- to generally investigate time triggered architectures,
- to investigate the implications concerning the development process,
- to implement synchronization mechanisms for the bus with the sensors and the bus with the ECUs,
- and to investigate consequences on the control performance and safety.

3 CAN-TTCAN-Gateway

Unfortunately, so far there does not exist sensors and ECUs which are capable to run TTCAN. Therefore, an intelligent PCB has been realized which realizes a CAN-TTCAN-Gateway.

3.1 Hardware Description

Figure 4 shows the top view of the CAN-TTCAN-Gateway. The board is based on the PowerPC micro controller MPC555. This controller provides on-the-chip various integrated sub systems, which earlier required additional external devices [AW99]. Some selected sub systems are two CAN controller and two TPUs (Time Processor Unit) which show the special emphasis to the automotive field. The real-time multi-tasking operating system RTOS-UH [Ger99] and the application programs reside and run in the internal flash EEPROM of the micro controller [WAG01]. A user program management allows to simply exchange user programs via a terminal interface. Furthermore, the board has been extended by a digital-to-analog converter and an ethernet module. Since the board makes two TTCAN chips [Har02] available, together with the two CAN controller of the MPC555 one can imagine the following applications of the board:

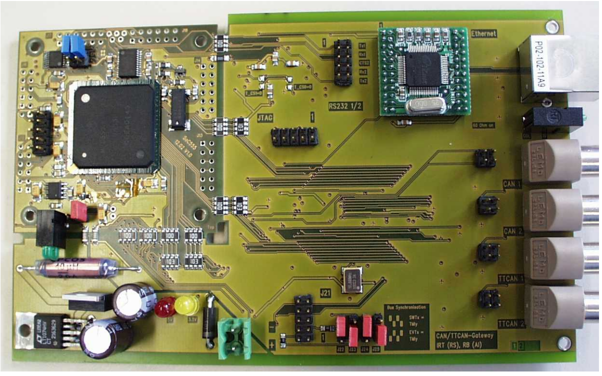

Figure 4: CAN-TTCAN-Gateway

- 2 independent CAN and 2 independent TTCAN nodes running control applications on the MPC555
- 2 separate one-to-one connections between CAN and TTCAN (the intended gateway functionality)
- 2 CAN-to-CAN-gateways (eventually with different data rates)
- TTCAN-to-TTCAN-gateway (see annotation above)
- fault-tolerant (synchronous) bus system with parallel TTCAN busses
- coupling of the busses to other media, like Ethernet, serial communication, etc.

For time triggered bus concepts the communication structure is defined in advance and generally not modified during operation. For that purpose the TTCAN chips are initialized at start-up by the content of a SPI-EEPROM (may be modified via the serial interface by implemented shell commands); afterwards, they operate autonomously. Merely the data of the messages may be modified during operation.

3.2 Migration from CAN to TTCAN

In order to explain the gateway functionality the simple architecture of figure 5 is considered. Here two CAN nodes (CAN node A and B) communicate via the CAN bus. Now the gateways are attached in between as shown in figure 6 (one board realizes two gateways).

From the point of view of the nodes nothing has changed, since both nodes still see merely a CAN bus. However, there is a dedicated receiver/transceiver to every node.

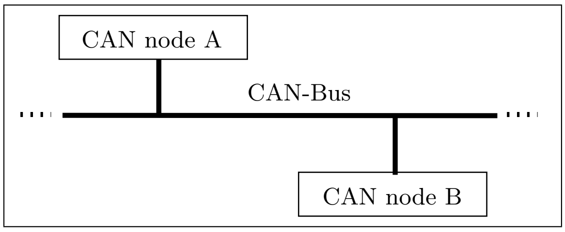

Figure 5: CAN bus with 2 nodes

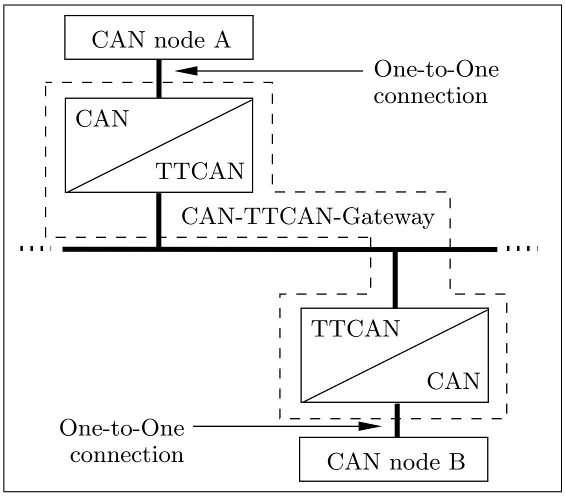

Figure 6: Migration from CAN to TTCAN

Thus, each node is attached to a one-to-one (private) CAN bus. From the point of view of the bus a time triggered communication has been established. The tasks of the gateway are to forward messages from the TTCAN bus to their dedicated receivers on the one hand and to place outgoing messages from the CAN nodes into the predefined time slices of the TTCAN bus cycle on the other hand.

3.3 Time behavior

Figure 7 illustrates the behavior of the gateway along the time axis for the scenario depicted in figure 6. A situation is shown, where a message for CAN node B arrives on the TTCAN bus (signal on the top level). The second signal represents the interrupt of the corresponding TTCAN chip. The falling edge of this signal indicates the time instance at which the TTCAN chip notices that a message arrived for node B. Now the gateway repeats this message on the one-to-one private CAN bus to node B (signal on the bottom level). The third signal from the top indicates with its falling edge the arrival of the data at their dedicated destination (typically a task that is waiting for the data).

The repetition of each message implies a latency. But since we have a one-to-one connection between the gateway and its dedicated node, the bus can always be accessed and messages are never delayed. As a result, the latency is constant[1], known and therefore considerable in advance. If one is concerned to send a message, the content of the message should be at hand the latency time earlier. If a node receives a message, in fact the message is a latency time delayed. These facts must/can be taken into account when designing the communication matrix for a TT system on the basis of the gateway.

The scenario in figure 7 shows a total latency of approximately 325μs. This was a result for the data rate 250 kbit/s. For a 1 Mbit/s system one can expect for an 8 byte message a latency of about 200μs. For the example application of the VDM which runs a cycle of 20 ms the latency is 1% and hence not very critical. Moreover, the latency can be considered in advance as already explained.

Summarizing, it is possible to emulate and to test a pure time triggered architecture if the addition constant latency is considered.

3.4 Synchronization Bus ↔ Sensors

Time triggered architectures work to a predefined schedule. Therefore, all participants like the bus, the sensors and the ECUs have to be time trigger compliant. Otherwise, for instance, it is not assured that measured data are up to date. In the worst case they can exhibit a time delay of an entire cycle time (see also [AG03]). But since the participating nodes typically possess different time bases (jittering crystal oscillators etc.) there is the necessity to synchronize all participants.

Usually for time triggered systems it is proclaimed that the bus serves as the time master and delivers the global time. All sensors and ECUs are then synchronized to this global time. In most cases a single synchronization in every global cycle suffices.

---

[1] Jitter occurs only when the IR is displaced. Since there is no further application except the gateway function, at most the timer interrupt can lead to a delay (μ seconds).

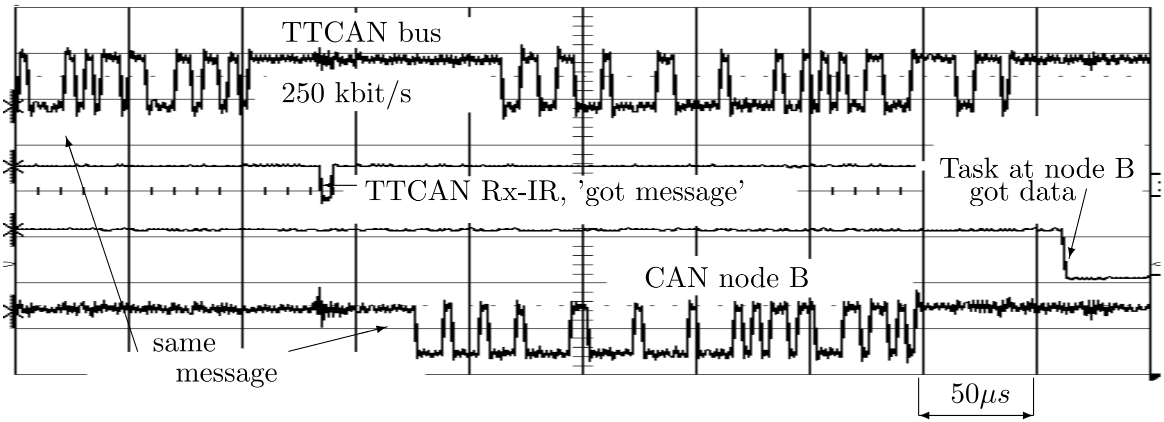

Figure 7: Time behavior of the CAN-TTCAN-Gateway (data rate of the CAN bus and the TTCAN bus each at 250 kbit/s).

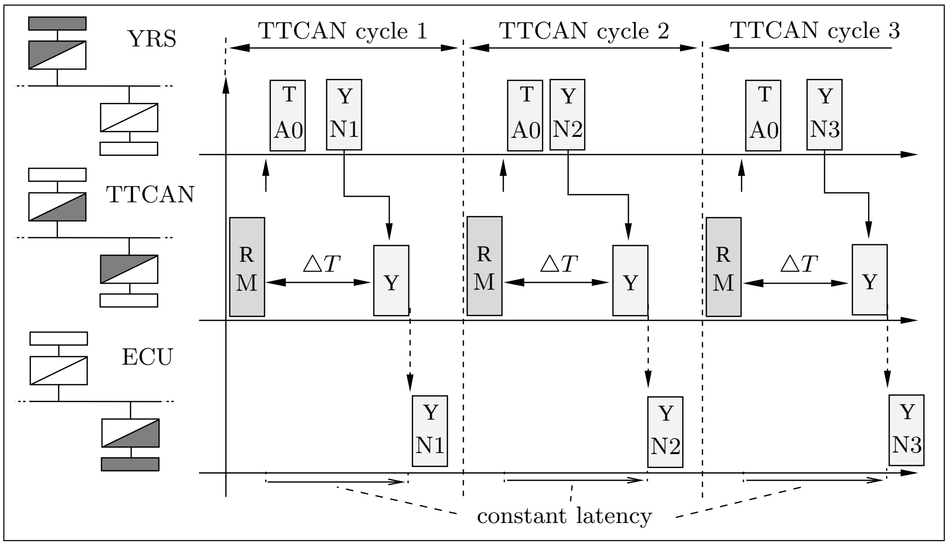

Figure 8: Synchronization of the yaw rate sensor MM1.1, resulting in a constant latency (annotation: time axis is distorted)

As an example for the usage of the gateway the synchronization of an ECU with the yaw rate sensor (YRS) via the bus is demonstrated in figure 8. It illustrates the actions of the different stations with respect to the cycle time on the TTCAN bus.

The utilized sensor MM1.1 is not purpose-built for time triggered architectures but as will be shown subsequently, a synchronization to the bus cycle is possible.

There are two versions of the yaw rate sensor. With the analog version we have no problem since we read the current measurement on demand. The digital version internally performs an analog to digital conversion and sends the result on request. To this end one has to request a measurement via a CAN message with a dedicated ID (0xA0 in figure 8). Triggered by this message the yaw rate sensor delivers the current measurement whereas the time delay between the trigger message and the result message is guaranteed to be below a certain time limit. It is therefore possible to make sure that at a certain time instance an up to date measurement is available. As shown in figure 8 one has to define appropriate time slices for the request and the response in the TTCAN cycle. As a result, a constant latency is assured between the trigger message (the request of the measurement) and the receipt of the data at the dedicated node. Constant and known latencies generally can be compensated by the control algorithm.

The time axis in figure 8 is distorted, since in the actual application the cycle time is in the range of 20ms whereas the constant latency is about 1.5ms.

4 Summary

By means of the VDM, the Bosch concept of vehicle dynamics management, a time triggered architecture and its effects on the hardware, the software and the development process should be investigated. At present, the control/functionality of the VDM is realized with the CAN bus. For the examination an exemplary migration to its time triggered version TTCAN is in progress. The project is roughly divided into four phases.

The first phase was dedicated to a basic comparison of the real time performance of event triggered and time triggered bus concepts. As explained in [AG03] it was possible to interpret the bus itself as a dynamic system and to measure its frequency response which allows the detection of characteristic properties of the bus system. For instance, the measurements yielded a reliability measure given by the average latency response time and the jitter when reacting to asynchronous external events.

The second phase was the subject of this paper. Since so far there are no sensors and ECUs which are capable to run TTCAN, an intelligent CAN-TTCAN-Gateway has been realized. In this way it becomes possible to emulate an entirely time triggered system. As was shown, merely constant but a priori known latencies have to be considered.

The last two phases of the project deal with laboratory and in-vehicle experiments. This includes, for instance, the already mentioned synchronization problem and the examination of the implication onto the development process. Furthermore, it is intended to investigate the effects on the control performance.

References

[AG03] A. Albert and W. Gerth. Evaluation and Comparison of the Real-Time Performance of CAN and TTCAN. 9th CAN in Automation Conference, iCC, Munich, 2003.

[APF02] L. Almeida, P. Pedreiras, and J. Fonseca. The FTT-CAN Protocol: Why and How. IEEE Transaction on Industrial Electronics, 49(6):1189–1201, Dec 2002.

[AW99] A. Albert and B. Wolter. Multitalent MPC555: Schneller durch Gleitkommaeinheit. Elektronik, (15):48–53, 1999.

[BBE+02] R. Belschner, J. Berwanger, C. Ebner, H. Eisele, S. Fluhrer, T. Forest, T. Führer, F. Hartwich, B. Hedenetz, R. Hugel, A. Knapp, J. Krammer, A. Millsap, B. Müller, M. Peller, and A. Schedl. FlexRay – Requirements Specification. FlexRay Consortium, Internet: http://www.flexray.com, Version 2.0.2, April 2002.

[CAN90] CAN. Controller Area Network CAN, an Invehicle Serial Communication Protocol. SAE Handbook 1992, SAE Press, pages 20341–20355, 1990.

[Ger99] W. Gerth. Handbuch RTOS-UH Version 4.2. Institut für Regelungstechnik, Universität Hannover, Internet: http://www.rtos.irt.uni-hannover.de/, 1999.

[Har02] F. Hartwich. TTCAN IP Module User's Manual, Version 1.6. Robert Bosch GmbH, Automotive Equipment Division 8, Development of Integrated Circuits (MOS), 2002.

[KLS99] M. Knoop, K.D. Leimbach, and W. Schröder. Increased Driving Comfort and Safety by Electronic Active Steering. SAE Active Safety TOPTEC, 27.-28.09.1999, Vienna, pages 1–8, 1999.

[KLV99] M. Knoop, K.D. Leimbach, and A. Verhagen. Fahrwerksysteme im Reglerverbund. Tagung Fahrwerktechnik, Haus der Technik, Essen 17.-18.03.1999, pages 1–10, 1999.

[Kop97] H. Kopetz. Real-Time Systems – Design Principles for Distributed Embedded Applications. Kluwer Academic Publishers Boston/Dordrecht/London, 1997.

[Kop00] H. Kopetz. A Comparison of CAN and TTP. Annual Reviews in Control, 24:177–188, 2000.

[LH02] G. Leen and D. Heffernan. TTCAN: A New Time-Triggered Controller Area Network. Microprocessors and Microsystems, 26(2):77–94, 2002.

[LKK03] P. Leteinturier, N.A. Kelling, and U. Kelling. TTCAN from Applications to Products in Automotive Systems. Proceedings of the SAE International Conference, paper ID 2003-01-0114, pages 1–10, 2003.

[MFH+02] B. Müller, T. Führer, F. Hartwich, R. Hugel, and H. Weiler. Fault-tolerant TTCAN networks. CAN Newsletter, CiA, pages 18,20,22,24,26,28, Juni 2002.

[Org] International Standardization Organization. ISO 11898-1 (Controller Area Network, Data Link Layer), ISO 11898-2 (High-Speed Transceiver), ISO 11898-3 (Fault-Tolerant Low-Speed Transceiver), ISO 11898-4 (Time-Triggered Communication).

[Ran02] M. Randt, editor. Workshop 'Bussysteme im Automobil', Electronics & Communication in Traffic Systems ECT2002. Internet: http://www.carbussystems.de/, Juni 2002.

[TL02] A. Trächtler and E. Liebemann. Vehicle Dynamics Management: Ein Konzept für den Systemverbund. 11. Aachener Kolloquium Fahrzeug- und Motorentechnik 2002, 2002.

[WAG01] B. Wolter, A. Albert, and W. Gerth. User-Expandable, On-The-Chip Real-Time Operating System for High Performance Embedded Mechatronic Systems. Proc. of the 1st IEEE Int. Conf. on Information Technology in Mechatronics, ITM'01, pages 255–261, Okt. 2001.

[Zan02] A. van Zanten. Evolution of Electronic Control Systems for Improving the Vehicle Dynamic Behavior. 6th International Symposium on Advanced Vehicle Control, AVEC 2002, 2002.

Dr.-Ing. A. Albert
Robert Bosch GmbH, Dept. FV/SLF
Robert-Bosch-Str. 2
71701 Schwieberdingen, Germany
Tel. +49(0)711/811-43607
amos.albert@de.bosch.com

Dipl.-Ing. R. Strasser
Institute of Automatic Control, Uni Hannover
Appelstr. 11, 30167 Hannover, Germany
Tel. +49(0)511/762-3054
strasser@irt.uni-hannover.de

Dr.-Ing. A. Trächtler
Robert Bosch GmbH, Dept. FV/SLF
Robert-Bosch-Str. 2
71701 Schwieberdingen, Germany
Tel. +49(0)711/811-3958
ansgar.traechtler@de.bosch.com