The Development of a New Automotive Diagnostic Approach

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Abstract

This thesis describes the master by research project “The Development of A New Automotive Diagnostic Approach” and contains the current diagnostic approach, the own developed idea of a new diagnostic method and the hardware design of a new diagnostic tool for vehicles.

The messages of the sensors and control units are transmitted over the in-vehicle bus network and are different depending on the condition of the car. The new diagnostic approach uses our developed theory, that the bus level changes between faultless and faulty vehicle condition.

The thesis enables an understanding of the basic principles of automotive electrics, control systems and the subjacent fault diagnostic principles. To understand these complex diagnostic principles, the different protocols and standards are described.

A hardware interface to the in-vehicle bus system is shown which can be used for many different applications, like manipulating/monitoring existing CAN networks, as a diagnostic tool, creating own control systems or for automotive security experiments. The main components of the hardware are an Atmel AT90CAN128, the Philips CAN transceiver PCA82C251, the FTDI FT245BM USB FIFO and the VNC1L USB host controller. The interface developed in this project gets the same results as an up to date conference paper published for for IEEE.

Based on the shown in-vehicle bus interface in this thesis an idea of a new control system for cars is described. The idea is to control the tyre pressure during an automatic vehicle emergency break. The idea is a reduction of the collision speed and therefore a further reduction of the stress for the vehicle passengers and the resulting injuries for vehicle occupants.

Copyright statement

Acknowledgement

I would like to thank the School of Computing and Engineering at the University of Huddersfield for enabling this research project to be completed.

I express my gratitude to my supervision team of my research, Dr. John Shi as main-, Prof. Dr. Karsten Schmidt as co- and Prof. Andrew Ball as second supervisor, who have guided, helped and supported me throughout the project.

I also gratitude the technical staff in the electrical and automotive lab of the University of Huddersfield for the support in performing practical tests. The University of Applied Sciences Coburg for the supply of microcontroller development tools and assembling the circuit board. The University of Applied Sciences Schweinfurt for the manufacturing of printed circuit boards.

The work is very enjoyable and I would like to keep on working in the area of automotive electrics with a special focus on diagnostic and control system. The project supervisors and I are hoping that we can keep on going with one of the ideas which came up during the project as described in this thesis.

About the Author

Michael Selig studied on the University of Applied Sciences (UAS) of Coburg and obtained a B.Sc. degree in Automotive Information Technology. Based on an interchange agreement between the UAS Coburg and the University of Huddersfield, Michael Selig spent his final year in Huddersfield and obtained a B.Eng. (Hons) in Computer Control Systems.

His main interests are technical control systems and the communication between the related components. A special focus lies on control system of vehicles and the development of embedded systems.

He has industrial experience of programming and debugging automotive control units gained at the Kübrich Ingenieurgesellschaft, Germany.

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Glossary of Terms and Abbreviations

ABC	Active Body Control
ABS	Anti Lock Braking System
ACC	Adaptive Cruise Control
ADAC	Allgemeine Deutsche Automobil-Club e.V.
ADC	Analogue Digital Converter
AFS	Active Front Steering
ALU	Arithmetic Logic Unit
ASIC	Application Specific Integrated Circuit
CAN	Controller Area Network
CARB	California Air Resource Board
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access/ Collision Avoidance
CPU	Central Processing Unit
DRAM	Dynamic Random Access Memory
DSP	Digital Signal Processor
ECU	Electronic Control Unit
EEPROM	Electrically Erasable Programmable Read Only Memory
EPROM	Erasable Programmable Read Only Memory
ESC	Electronic Stability Control
EOF	End Of Frame
FAT	File Allocation Table
FIFO	First In First Out
GPL	General Public License
IEEE	Institute of Electrical and Electronics Engineers
ID	Identifier
ISO	International Organisation for Standardisation
JTAG	Joint Test Action Group
LIN	Local Interconnect Network

LKAS	Lane Keeping Assistance
MIL	Malfunction Indicator Lamp
MIPS	Mega Instructions Per Second
MOST	Media Oriented Systems Transport
MOT	Ministry of Transport test
MROM	Mask Read Only Memory
NI	National Instruments
NTC	Negative Temperature Coefficient
OSI	Open Systems Interconnection Reference Model
OTP	One Time Programmable
PROM	Programmable Read Only Memory
PTC	Positive Temperature Coefficient
PWM	Pulse Width Modulation
RA	Remote Address
RAM	Random Access Memory
RFI	Radio Frequency Identification
RISC	Reduced Instruction Set Computer
ROM	Read Only Memory
RTC	Real Time Counter
SAE	Society of Automotive Engineers
SOF	Start of Frame
SRAM	Static Random Access Memory
SPI	Serial Peripheral Interface
TCS	Traction Control System
TTCAN	Time Triggered CAN
USB	Universal Serial Bus
USART	Universal Asynchronous Receiver/Transmitter

Chapter 1

Introduction

The chapter “Introduction” provides basic information about the entering of mechatronic systems in vehicles as well as the history of the diagnostic concepts used over the past years.

1.1. The history of mechatronic systems in vehicles

In the beginning of the 1980s computer technology was introduced in automobiles. That means the development in the automotive industry changed from the classical field of mechanical engineering to a new discipline, called mechatronics, (Richter, 2005).

The term mechatronic was firstly used in Japan by the company Yaskawa Electric Corporation in 1969. Mechatronic means the combination of the mechanical-, electronic-, control systems and the computer technology. The merging of the different disciplines has the benefit of synergistic effects in the development of new products. Figure 1.1 illustrates the structure of the field mechatronics with its different subareas, (North Carolina State University, 2010), (Brown, 2008).

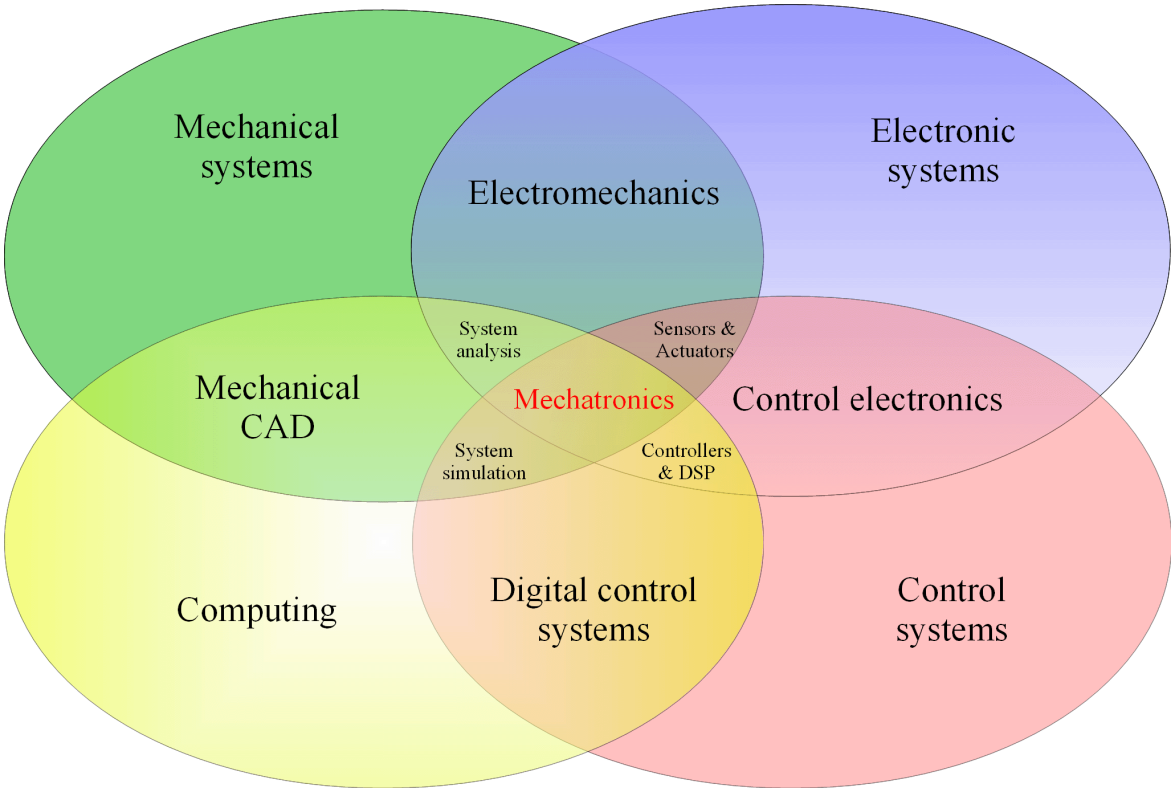


Figure 1.1: The make up of mechatronics

Reasons for the initiation of mechatronic systems in cars are the improvement of comfort, safety, and reliability of vehicles in cooperation with advanced fuel consumption, better car handling, and the reduction of emissions and the production costs.

Another reason is the available construction space for new systems in cars which is limited in the aspects of car design, aerodynamic efficiency and the increasing traffic. Figure 1.2 shows the augmentation of construction space for new technologies with conventional development methods compared to the needed construction space with the use of the mechatronic method, (Gevatter/Grünhaupt, 2005).

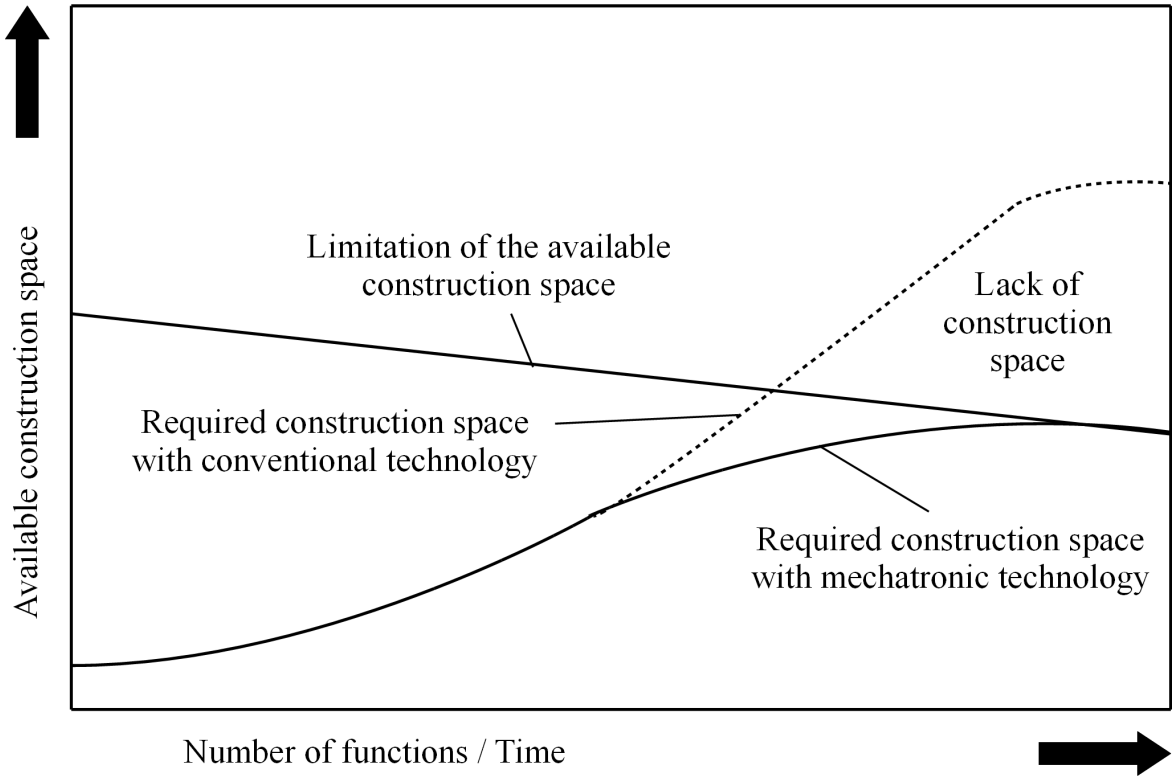


Figure 1.2: Construction space vs. Number of functions/Time

In the majority of cases mechatronic systems are used to control a mechanical task. Basically the system consists of sensors, a control unit (based on a microcomputer system) and actuators. The sensors are measuring physical properties and transferring the information to the control unit. The control unit compares the value of the sensor (called actual value) with a given desired value. In case of deviation, the control unit sends a command to an actuator to execute a defined task. This basic principle of a mechatronic control system is illustrated below.

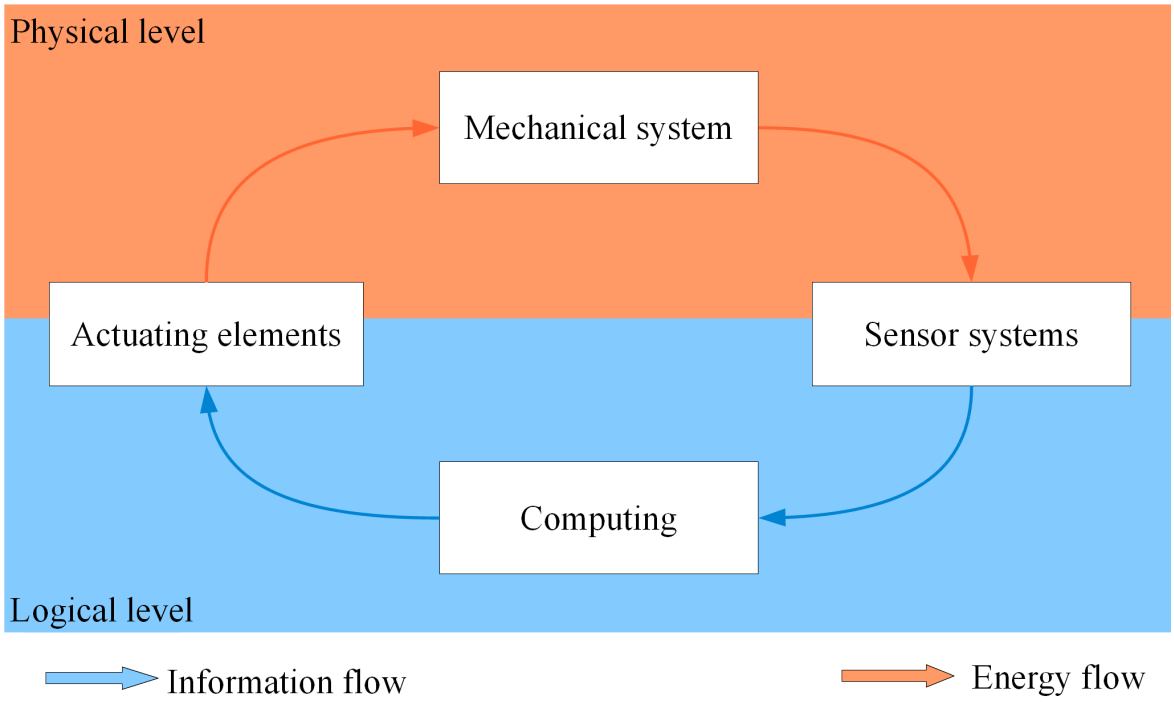


Figure 1.3: Information/Energy flow in a mechatronic system

To point out the development of mechatronic systems in cars an overview since 1979 is listed in chronological order:

- Cruise Control (1979): Controlling the vehicle speed with a speed sensor and an electrical wire rope.
- ABS (1979): Anti lock braking system to avoid locked tyres while braking. Thereby the car stays steerable.
- TCS (1986): Traction control system to prevent loss of traction of the driven road wheels. The control of the vehicle is maintained when the throttle is extensive applied and the road surface can not handle the applied torque.
- ESC (1995): Electronic stability control to prevent the car from skidding by braking individual wheels.
- ACC (1999): Adaptive cruise control uses the radar technology to control the vehicle speed and the distance to the car in front.

- ABC (1999): Active body control means the extension of the suspension with hydraulic actuators to improve the vehicle rolling behaviour.
- LKAS (2001): Lane keeping assistance warns the driver if the vehicle begins to move out of its lane.
- AFS(2003): Active front steering balances the steering angle when side wind occurs or on interventions of the ESC, (Bosch, 2007b).

In current luxury cars (e.g. Mercedes S class, BMW 7 Series, Audi A8) are over 80 electronic control units installed depending on the configuration and the installed equipment, (Meroth/Tolg, 2008).

The innovation and the development in the field of mechatronic systems is not finished yet and the part of the electronic cost still increases. In 2010 the electronic costs are 40% of the overall costs in a premium car which is illustrated in figure 1.4, (Gevatter/Grünhaupt, 2005).

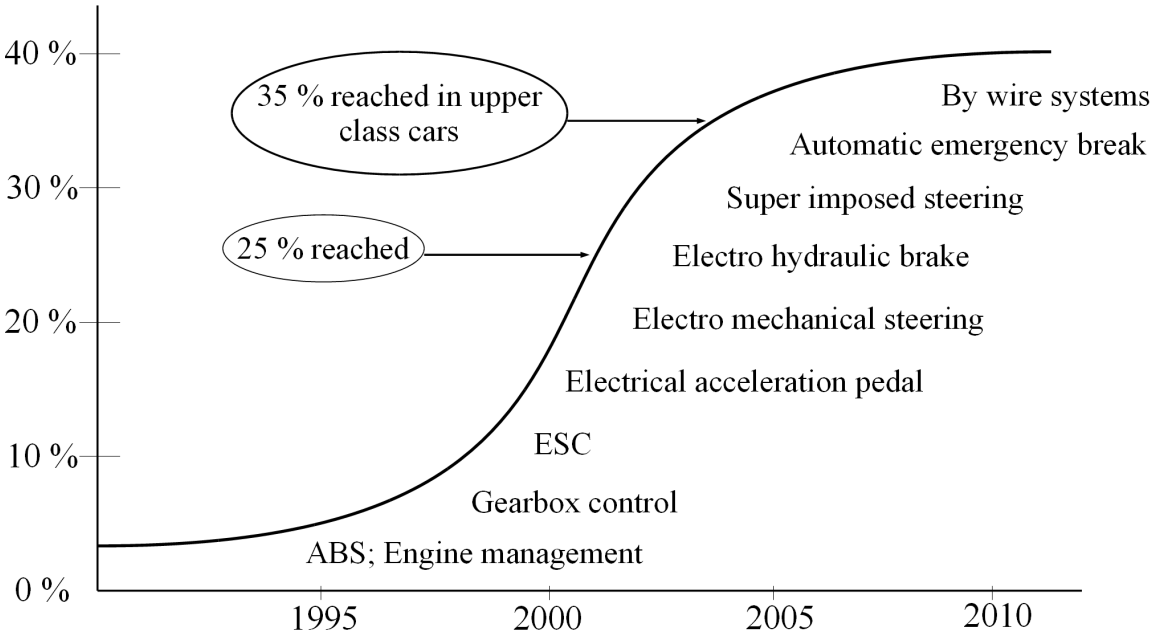


Figure 1.4: Portion of electronic costs of vehicles

The x by wire systems will cause a further increase of mechatronic systems in future cars. At the moment the focus lies in the development of steering by wire and braking by wire systems, (Jurgen, 2009).

1.2. The cross linking of the control units

With the initiation of electronic control systems like ABS and engine management in the beginning of the 1980s it was necessary to create an in-vehicle (onboard) communication method. The first approach was a point to point connection and the communication is carried out using analogue or switch signals.

Also a communication between the control units and offboard tools, like diagnostic tools (used in garages) or tools in the manufacturing process for flashing electronic control units (ECU), is needed to exchange data. Bosch as a leading company in developing and producing ECUs published a communication specification which was adopted by many car manufacturers. The specification is similar to the serial interface RS232 of PCs and defines the the number of connection wires, the electrical signal level and the bit format of the signal transmission. Later the specification was standardised in the ISO 9141 specification, (Bosch, 2007a).

With the introduction of the CAN bus in the beginning of the 1990s it was from now on possible to have a fast onboard data exchange in vehicles. The CAN bus was developed by Bosch in cooperation with Intel and standardised in the ISO 11898 Road Vehicles – Controller Area Network and the SAE J1939, (Zimmermann/Schmidgall, 2007).

The different tasks of the control units have opposite requirements like bandwidth, redundancy, fault tolerance and response time. Therefore various bus protocols are developed and used in cars like CAN, TTCAN, MOST, byteflight or LIN.

1.2.1. Terminology of bus systems

Cross linking

Commonly the data transmission is executed bitwise and serial. The easiest way is a direct connection between two control units. Figure 1.5 shows the correlation, (Zimmermann/Schmidgall, 2007).

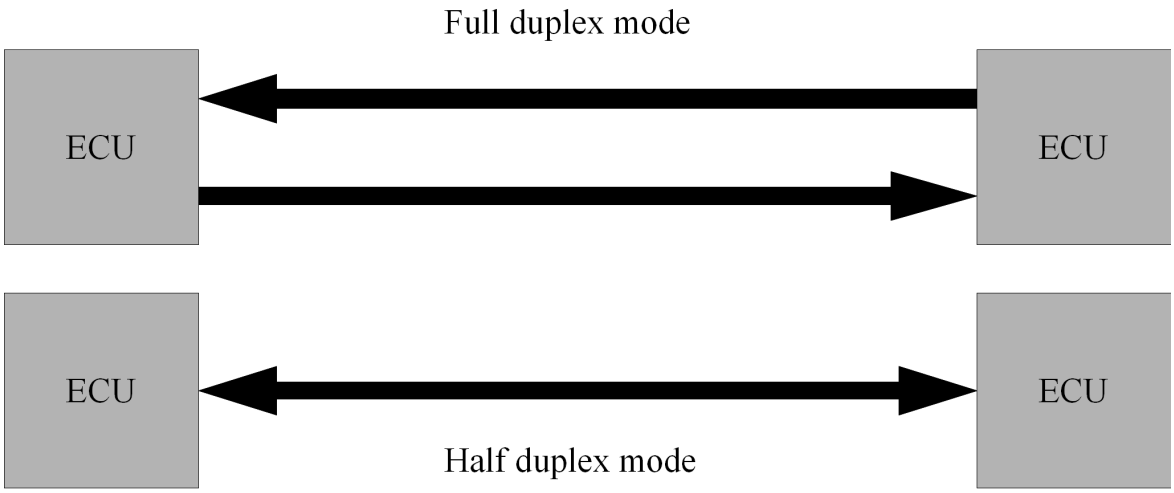


Figure 1.5: Full and half duplex mode

Depending on the use of a shared bidirectional line or a pair of unidirectional lines, the data transmission takes place in half duplex or in full duplex mode between the control units.

- Full duplex mode: Sending and receiving data is possible at the same time.
- Half duplex mode: Alternate sending and receiving data of each control unit.

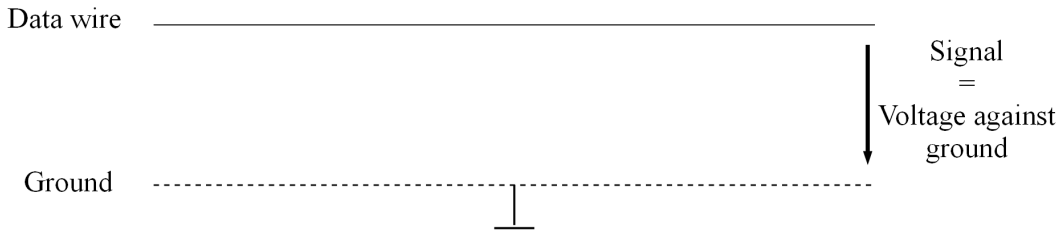
The cross linking is realised either with one wire or two wires, shown in figure 1.6:

One wire connections: Are cheaper in aspects of cost and the signal recirculation takes place over the car body, which is also the signal earth. This kind of linking is very fragile in aspects of electromagnetic compatibility. Hence high signal levels and low bit rates are applied. Often the supply voltage is used as signal level in automotive applications. Example bus systems using the one wire technology are the LIN bus and the ISO 9141.

Two wire cable: Are often twisted and not as fragile in aspects of electromagnetic compatibility as one wire cables. This allows higher bit rates and small signal levels.

Figure 1.6 explains the meaning of a signal in a one wire and a two wire linking.

Single wire bus connection:



Two wire wire bus connection:

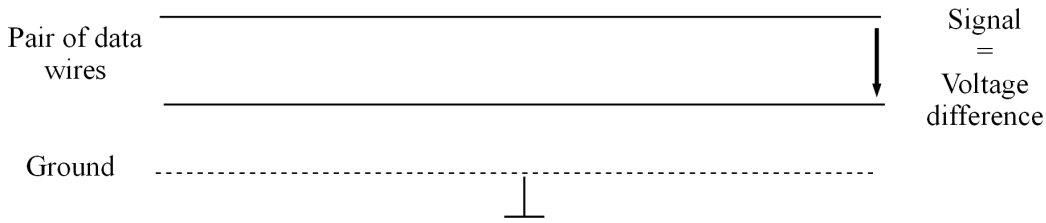


Figure 1.6: One and two wire bus connection

Topology, network types and structure

Contrary to the point to point connection of only two ECUs, in a network several numbers of control units are connected to each other. Therefore different topologies exist. Mainly used is the bus which is nowadays a synonym for data networks in vehicles.

A bus topology is created when several control units are connected to the same data wires, shown in figure 1.7. Bus access methods have to control which connected control unit has the permission to send data. Otherwise collisions are occurring. Bus access methods are explained later in this chapter.

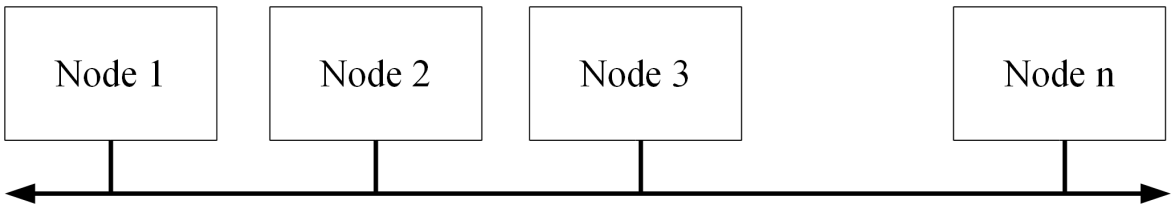


Figure 1.7: Bus topology

Multimedia networks like MOST use a ring topology. FlexRay supports the star structure beside the normal bus topology. A broken bus user in the ring topology means a breakdown of the whole network as well as a broken star node in the star network, which are the disadvantages of these topologies, (Meroth/Tolg, 2008). Figure 1.8 shows the structure of the ring and star topology.

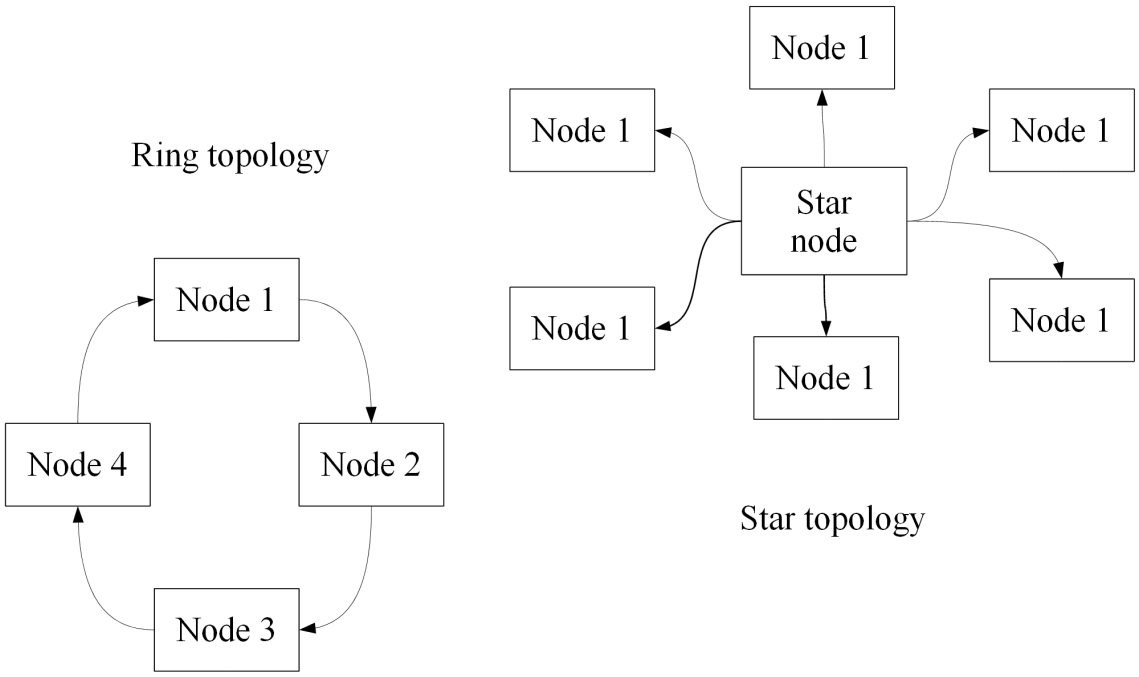


Figure 1.8: Ring and star topology

Physical Layer

The physical layer is the connection of the control units to a network, which enables the control units to send and receive data. As medium can be used wires (e.g. copper, aluminium), wireless technology (e.g. Bluetooth, ZigBee) or optical material (synthetics, fibre glass) which has a better electromagnetic compatibility. Disadvantages of optical material are temperature instability, a low tensile strength and the high costs.

Due to the mass production of cars and the high number of control units it is economical for vehicle and semi conductor manufacturers to integrate the physical layer as transceiver devices in the layout of the control unit.

Codification: The physical layer describes also the interpretation of the signal level (the potential) shown in figure 1.9. The codification is divided between two methods called non return zero NRZ and Manchester code.

NRZ codification is applied when in the duration of a bit the potential does not change. The disadvantage of NRZ is the possibility of loosing the synchronisation between sender and receiver when a sequence of identical bits occurs. This disadvantage is compensated by the Manchester code. The Manchester code interprets a rising and a falling edge of a chancing potential as a bit. Compared to the NRZ, the data rate of the Manchester code is therefore only half the speed, (Wallentowitz/Reif, 2006).

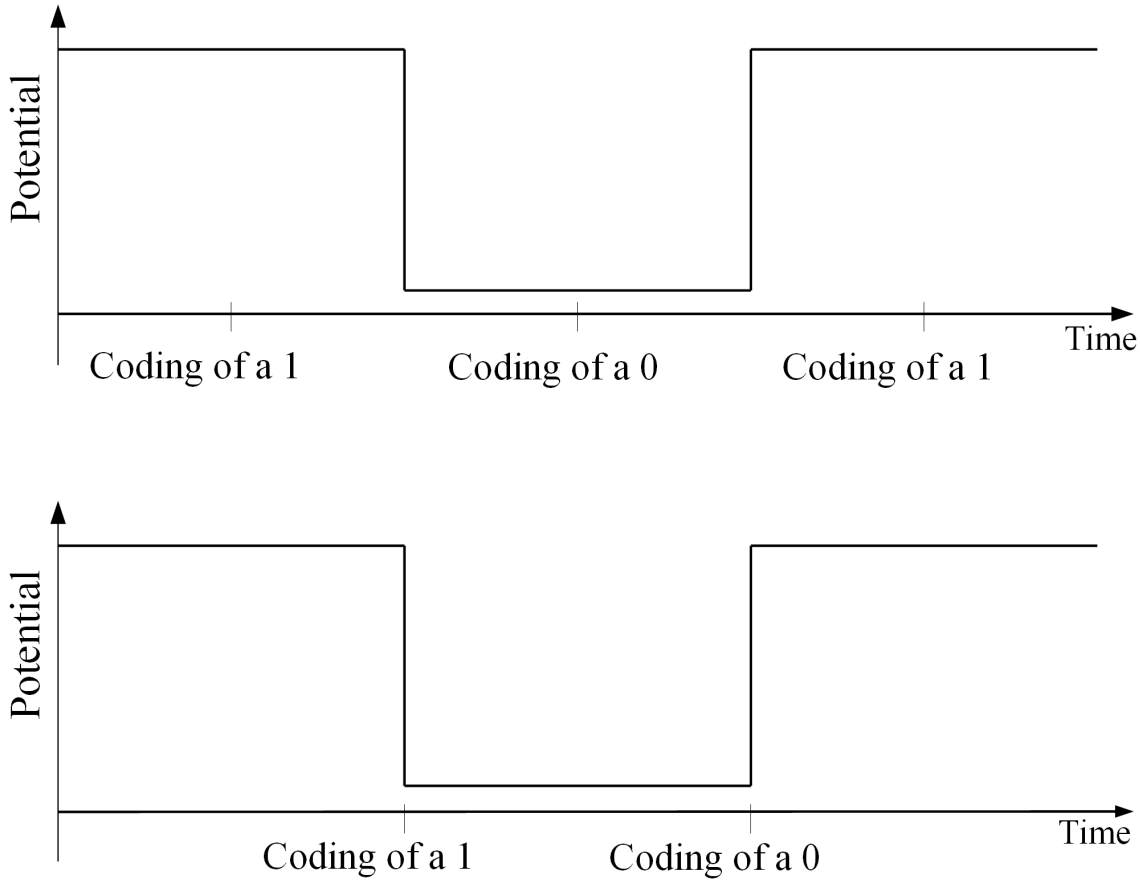


Figure 1.9: NRZ and Manchester coding

Data rate

The data rate is the transmission speed of single bits and defines how many bits can be transmitted in one second. Hence the unit is “bit per second” or derived units like kBit/s or MBytes/s (1 Byte = 8 Bit, 1kByte = 1024 Byte).

Bus access methods

Master Client and Multi Master model: In the master client model one control unit acts as master and controls the communication with periodic polling of the connected slaves. An example network using the master client method is the LIN bus. The master communicates with the slaves in configured time sequences. This method guarantees a data transmission in a predicted time. The time between the initialisation of a message by the sender and the arrival at the receiver is called latency time. Networks with a predictable latency time are deterministic.

In multi master networks every control unit has the same rights. This method is also called event triggered. An example of a multi master network is the CAN bus. In reality not every control unit and every message has equal rights. Hence messages are prioritised using identifiers. In event triggered networks the latency time is not predictable, therefore these networks are not deterministic.

Beside the time and event triggered methods systems exist, which combine the advantages of both earlier described methods. An example is the bus system FlexRay.

In the data communication of an event triggered network with multi master model it is possible that two control units want to send data at the same time. This method is called carrier sense multiple access CSMA.

It is differentiated between the CSMA/CD (collision detected) and CSMA/CA (collisions avoidance) model.

CSMA/CD: This method is not deterministic, because all messages have equal rights and can have a collision with another message. Hence it can not be guaranteed how long a message transmission takes. In the case of a very large bus load it is possible that no data are transmitted due to permanent collisions.

CSMA/CA: This method is used in vehicle applications, for example the method is implemented in the CAN bus. In case of a collision (two sender want to transmit a message at the same time) the message with the higher priority wins the arbitration procedure. The priority is implemented in the header of the message. This method guarantees deterministically for high priority messages.

Synchronicity: To assure an error free communication the receivers must be able to detect the start and the end of a data frame. It is differentiated between synchronous, asynchronous and isochronous data communication. Synchronous communication is performed with a clock signal. In asynchronous communication the data frame is fitted with start and stop bits.

A further access method is the time division multiple access TDMA. TDMA has a strict time schedule with time slots for every control unit. Only in this time frame the control units are allowed to transmit data. Control units which have to send more or high priority data get more or longer time slots. This communication method is deterministic and especially suitable for periodical data transmission e.g. measured sensor values in control loops. But it has disadvantages for seldom, spontaneous or for very urgent messages.

The TDMA method is used by FlexRay and TTCAN. But some control units need an interface for an asynchronous bus access as well due to the mentioned disadvantages.

Systems with different gaps in the time slots, like the TDMA method, are called isochronous, (Wallentowitz/Reif, 2006), (Zimmermann/Schmidgall, 2007).

1.2.2. Cross linking example

This part of the thesis describes which bus protocol is used for which automotive cross linking division as well as the main characteristics of the bus systems. In chapter 3.2 the CAN protocol is described in more detail, because the research project was focused on this communication protocol.

In the following a basic cross linking of the vehicle is shown. Of course, it differs of the characteristic, the manufacturer and the fitted equipments of the car, (Gevatter/Grünhaupt, 2005).

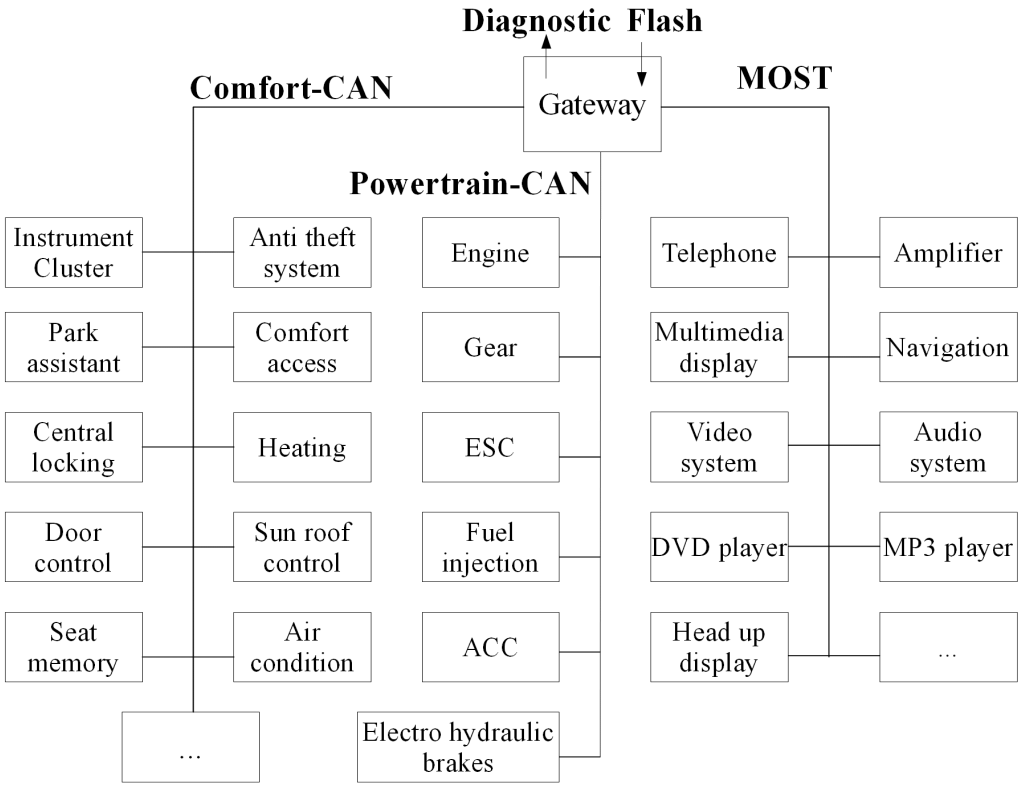


Figure 1.10: Automotive cross linking

The vehicle cross linking is structured in the divisions of powertrain, comfort, multimedia and manufacturer depending chassis and safety devices.

The communication between the engine and the gearbox, adaptive cruise control, the electronic control unit and others takes place using the CAN bus. A typical applied data rate is 500 kBaud. Experience of the manufactures showed that this bandwidth is enough to control vehicle speed, engine management or safety interventions of the ABS or ESC system, (Gevatter/Grünhaupt, 2005).

In the comfort area the CAN bus is often used as well, but in a low speed version. That means the bandwidth is reduced, because comfort systems like the air condition do not need to be controlled with a fast reaction time. The LIN bus is also used for comfort application.

The MOST bus uses an optical high-speed medium to exchange data and is used in the areas of audio, video, telephone and navigation. These applications need a high bandwidth due to the high amount of the required data to perform the tasks.

The bus systems byteflight, FlexRay and TTCAN are developed especially for safety systems. BMW started with Motorola, Elmos and Infineon to develop byteflight which was basically the first version of FlexRay. The FlexRay bus was created later in a consortium of the companies BMW, Mercedes Benz, Motorola and Phillips in 2000. In the years between 2001 and 2004 the companies Bosch, General Motors and Volkswagen joined the group as well. The byteflight and FlexRay protocol are used to transmit safety relevant data of the acceleration and pressure sensor, recognition of the used seats in the car, safety belts systems and data of the electronic system. For the transmission a noise secure fibre glass wire with a fast response time is used. The data rate is up to 10MBit/s with a cyclic time of 250 µs. All data messages are available for each connected note at the same time, similar to the CAN system. But every connected bus user obtains a specific time to send data called TDMA. This kind of bus access is free of collision and guarantees hard real time capability. TTCAN has also the ability to perform hard real time tasks but with the limited data rate of 1Mbit/s. TTCAN was not successful to perform safety relevant tasks, (Bosch, 2007a).

The interlinking of the different divisions and bus systems is carried out over gateways, also shown in the figure 1.10, (Gevatter/Grünhaupt, 2005).

1.2.3. Classification of bus systems

The SAE classifies the different systems for serial data transmission in three classes A, B and C. But nowadays this classification must be extended with safety relevant and multimedia systems which are shown in figure 1.11, (Wallentowitz/Reif, 2006).

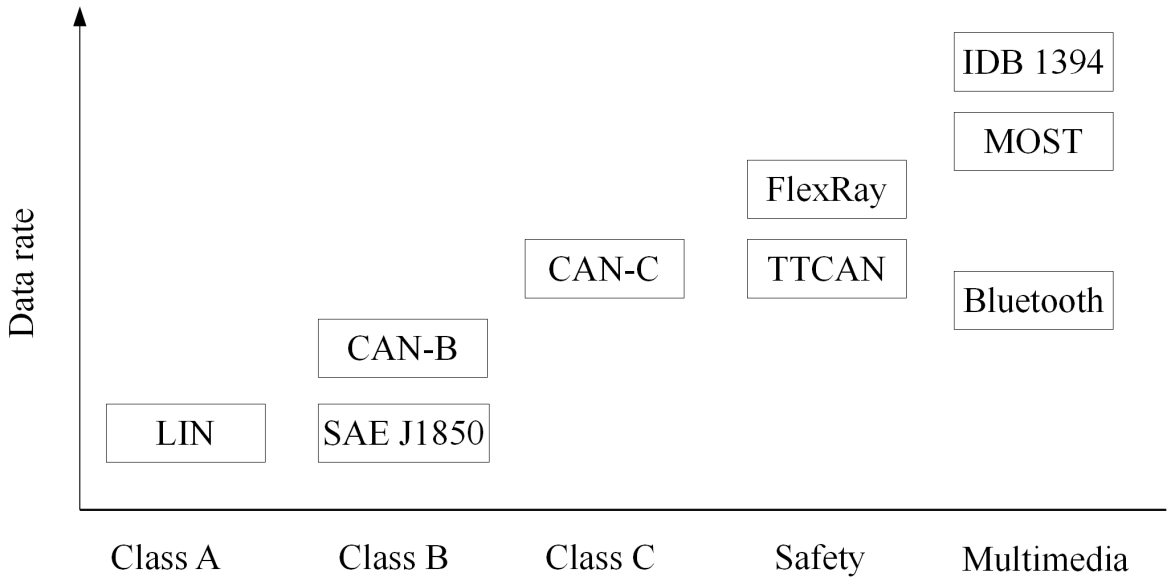


Figure 1.11: SAE bus classification

- Class A includes systems with low requirements on data rate (till 20 kBit/s), bandwidth and faultless transmission like the LIN bus.
- Class B includes bus systems to connect mainly control units of the car body like air conditioning or seat settings. A typical bus system is the low speed CAN, also called CAN-B due to the SAE classification.
- In class C the data rate and fault tolerance are relevant parameters. The standard bus system for this class is the high speed CAN, also called CAN-C due to the SAE classification. The high speed CAN connects for example the control units of the powertrain like the engine management, gearbox and brake control. The maximal data rate is limited to 1 Mbit/s but common is 500 kBit/s in the automotive industry.
- The next higher class regarding the requirements of data rate, determinism and fault tolerance are the communication networks for safety relevant functions. Examples are the time triggered and redundant systems like FlexRay and TTCAN.
- The highest requirements regarding data rate have infotainment/multimedia systems. Examples for this group are MOST and IDB-1394, (Wallentowitz/Reif, 2006).

1.2.4. Gateways

A single network which satisfies all requirements in vehicles on data rate, determinism, fault tolerance and especially costs is not realisable with the current available technology. Therefore different methods and technologies are applied to create new innovations. For example CAN-B is used for comfort applications and CAN-C in the powertrain and assistance systems. Also complex functions are often implemented over several control units in different networks. That requires a physical and logical gateway between the different networks. Gateways provide the data across the vehicle. The gateway functionality can be implemented in an extra control unit or integrated in an existing unit. For example the LIN master carries out the function of a CAN-LIN gateway. Figure 1.12 shows partly the network of a Volkswagen Golf V with the use of a central gateway. The central gateway provides also the access for the offboard diagnostic communication. (Zimmermann/Schmidgall, 2007).

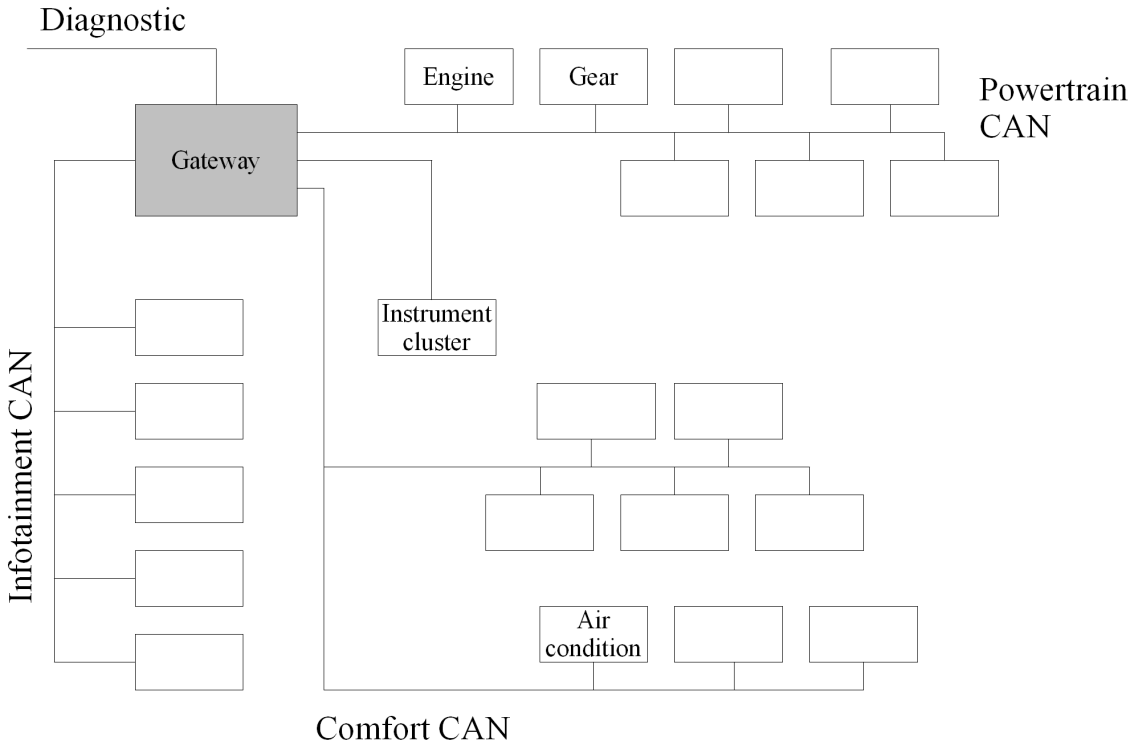


Figure 1.12: Bus gateway

1.3. The diagnostic in vehicles

The word diagnosis is Greek and means “apart-split to learn, knowledge” and is basically known from the medicine side. In medicine the term is used to identify the nature and the cause of an illness. In the same way the term is used in the automotive sector and the main aim is to remove the causes of a fault and the resulting symptoms, (Burchfield, 1994).

The diagnosis in the automotive sector exists as long as vehicles were invented, but changed fundamentally over the past years. In the beginning the diagnosis was carried out by a visual inspection of the mechanical parts of the car. With entering of electrical components the diagnostic method changed fundamentally and new tools are required. The first approach was to use basic measurement tools for example to check the ignition system where the mechanist had to interpret the test results. But this approach changed with the entering of electronic systems in a wide range to perform safety and comfort functions, explained in chapter 1.1. To handle these functions several control units are needed whereupon single functions/tasks are not implemented in an separate control unit but rather distributed over different. This fact needs a wiring of the control units explained in chapter 1.2. and makes the diagnosis complex.

First of all it has to be differentiated between two different approaches, named the onboard (OBD) and the offboard diagnosis.

On the self diagnosis the control units are permanently checking their own condition and the condition of the controllers surrounding. This is done either periodically in a program loop or when a corresponding boundary condition happens, hence when presumably a problem occurs. A typical example of the self diagnosis is the OBD, initiated by the U.S. legislative body. The OBD permanently reviews the cars emission information. For that matter all measured variables must be checked for compliance to specific threshold values. The threshold values are depending on the specification and the operating condition. Exceedings of the thresholds will be reported to the driver via a warning lamp in the dashboard of the car. The malfunction indicator lamp (MIL) in the dashboard helps to remove the problem quickly. Also the faults are permanently stored in the control unit to track the problem at a later date. To read the fault message a tester is used, which is an example for the offboard diagnosis.

The offboard diagnosis deals always with reading the trouble information of the vehicle and the appropriate handling of the fault. The first self diagnostic systems were very easily implemented using a light (either as an external device or internal warning lamps, like the ABS warning lamp in the dashboard) and blinking codes as fault indicator to isolate the fault location. This form of indication simplifies the fault localisation for the mechanist.

More complex systems with many control units, different sensors and actuators require a more accurate diagnostic option. The approach with the fault isolation is not enough any more and a better fault description was required. Therefore explicit rules had to be defined, which symptom creates a fault entry. An example is a too high voltage on the controller input. The fault entry can be displayed in the test tool with advices of reparation procedures.

Current systems with a variety of control units are distributed over the entire vehicle and communicate with each other via different bus systems. The systems are developed by different manufacturer and have functions distributed over several control units. This complexity implies high requirements for an accurate diagnosis. A single fault can affect several different control units caused by the network. This is illustrated in a following theoretical example:

A control unit detects a sensor error. As a result an error entry is made in the fault memory through the program for the automatic, frequently review of the sensor. At the same time several other controllers are depending on the output signal of the affected control unit. The messages of the affected control unit are no longer transmitted or no longer correct (implausible values) on the bus and other control units will make an error entry in their fault memory as well. The offboard diagnostic tool will read to the real error a lot more trouble code, made by different routines, which neither correlate in time nor content. The task of the diagnostic tool is to infer from the error messages to the actual fault, (Wallentowitz/Reif, 2006).

Thereby the car manufacturers using expert systems with different methods in the diagnostic tools to represent the faults:

- Case based systems: Have a fault matrix which describes the context of the fault and the associated fault solution. The system compares the given case with a similar possible case in the fault matrix. The concept of affinity is the key problem of such systems, due to its lack of precision.
- The inferencing rule: Is based on the “if clause” statements and the corresponding “then clause”. These systems are based on expert rules made of many inference rules. The system uses the rules to make a conclusion. Every rule is a unit and rules can be added and deleted without effecting already existing rules. But new rules or deleted rules have influence of the conclusion. This kind of fault detection is an advantage compared to the case based method because it is closer to human reasoning.
- Tree node interface: This approach receives information from the external world. The executer of the test provides the required information in form of a decision tree which is shown in figure 1.13.

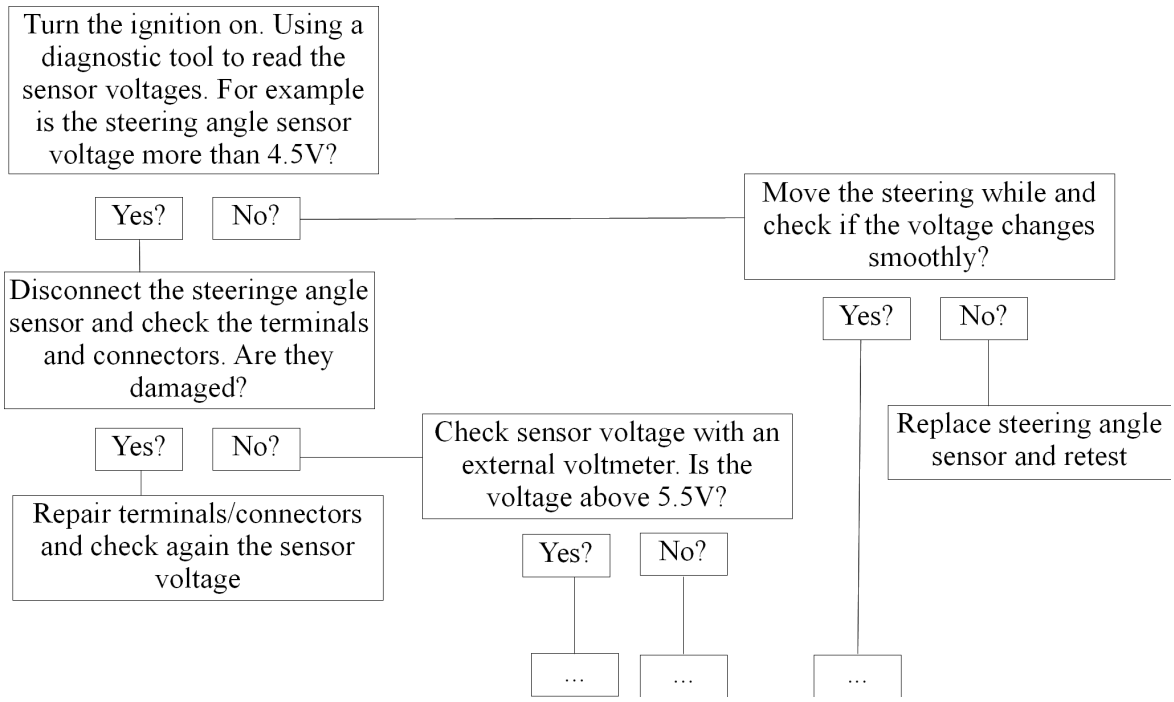


Figure 1.13: Decision tree example

The benefits of the tree node interface are the possibility to track the path of the fault solution and improve the decision tree by self study. The biggest problem of this method is the correct choice of the node attributes, (Bosch, 2007c).

The aim of all approaches is obviously a fast reparation of the car and a success in the first attempt. But the main aim is to avoid any faults and increase the car reliability. The diagnostic is an important, probably the most important part to achieve this aim. Therefore diagnostic methods will be improved and researched, (Denton, 2004).

Chapter 2

Aims & Objectives

This chapter describes the aim and objectives of the project "The Development of a New Automotive Diagnostic Approach".

Vehicle inspection is an annual test of automobile roadworthiness-, safety- and exhaust emission aspects undertaken by the MOT in Great Britain. Beside the mechanic condition the current status of the automotive electronics is checked. This review takes place by reading the fault memories of the electronic control units in the car.

The following diagram shows the percentage frequency of individual car components, which are responsible of automotive malfunctions in 2005 (ADAC, 2005) and 2008 (ADAC, 2008). The data are based on the statistics of the biggest automobile club in Europe, the ADAC.

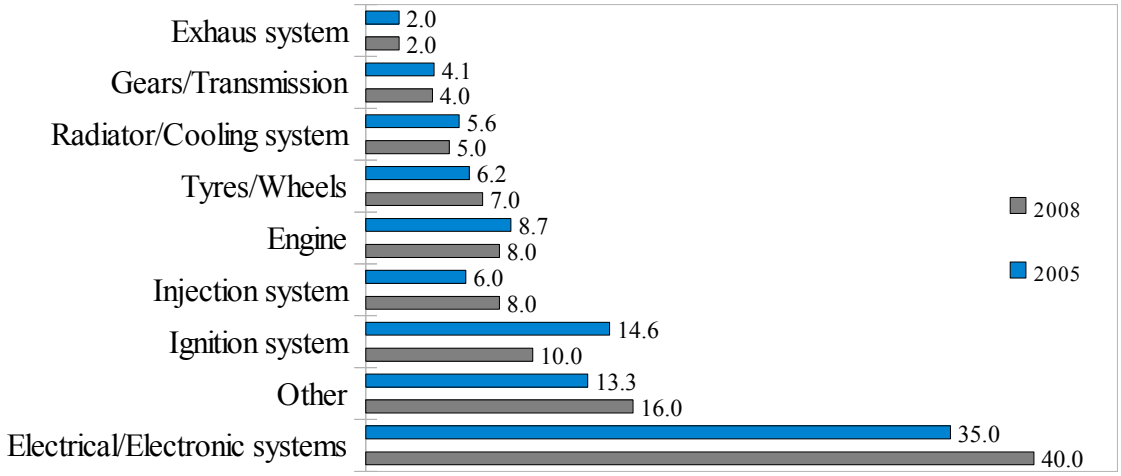


Figure 2.1: Automotive malfunctions in percent between 2005 and 2008

Figure 2.1 clarifies that the main reason for automotive malfunctions in 2005 and 2008 are the group of electrical and electronic systems. The responsibility of this group for vehicle breakdowns even increased of 5.0% in the shown period.

The next figure shows the newest statistics of automotive malfunctions where the overall electrical systems is the main reason with 60%, (ADAC, 2009). The group overall electrical systems includes the battery, the generator, the ignition, the engine management and all other electrical components.

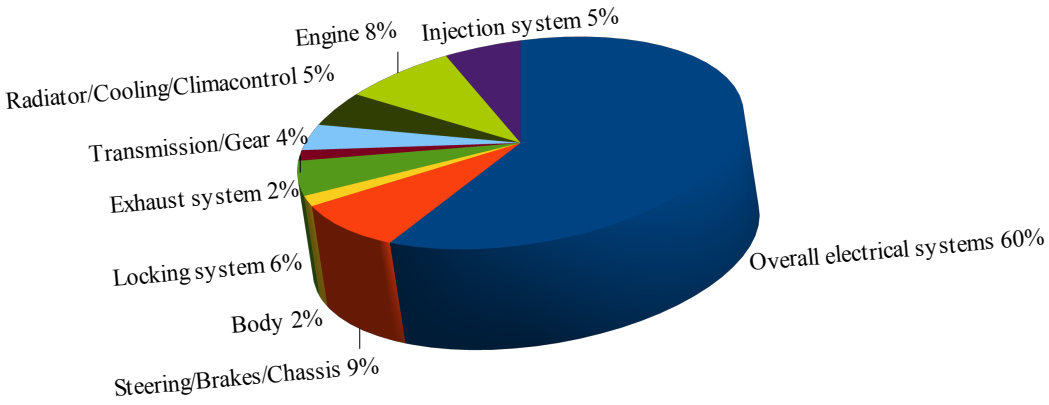


Figure 2.2: Automotive malfunctions in 2009

Due to the fact of faulty electronics as the main cause of automotive malfunctions car manufactures, sub contractors and universities are interested to face this problem.

To improve the electrical systems the faults are analysed. Therefore the detected defects by the control unit are stored in a fault memory embedded in the control unit. The fault description can be accessed using diagnostic tools.

The aim of this project is to create an advanced approach to detect mechatronic faults in cars. Hence the objectives are:

- **Objective 1:** Investigate the historical and current concepts used for automobiles diagnostics.
- **Objective 2:** Development of an advanced diagnostic approach.
- **Objective 3:** Design the hardware of a prototype diagnostic tool using the new developed approach.

Chapter 3

Background of automotive electronics

This chapter discusses the state of the art electronic systems including the CAN bus and the current diagnostic approach in detail. It clarifies the complexity and problems of the present diagnostic approach.

3.1. The principle of an electronic control unit

The tasks of control units in cars are totally differing depending on the function but the basic design is very similar. The task of a control unit is to process sensor data and adjusting actuators using a control algorithm. In figure 3.1 the basic structure of a control unit is shown and the control unit consists of:

- The CPU to process the control algorithm.
- Interface circuits for special sensors and actuators which is tried to standardised (e.g. using the bus systems CAN/LIN etcetera of the car). But there will be always sensors and actuators with special requirements on the communication interface.
- A transceiver as communication interface to other control units and service tools.
- A power supply.

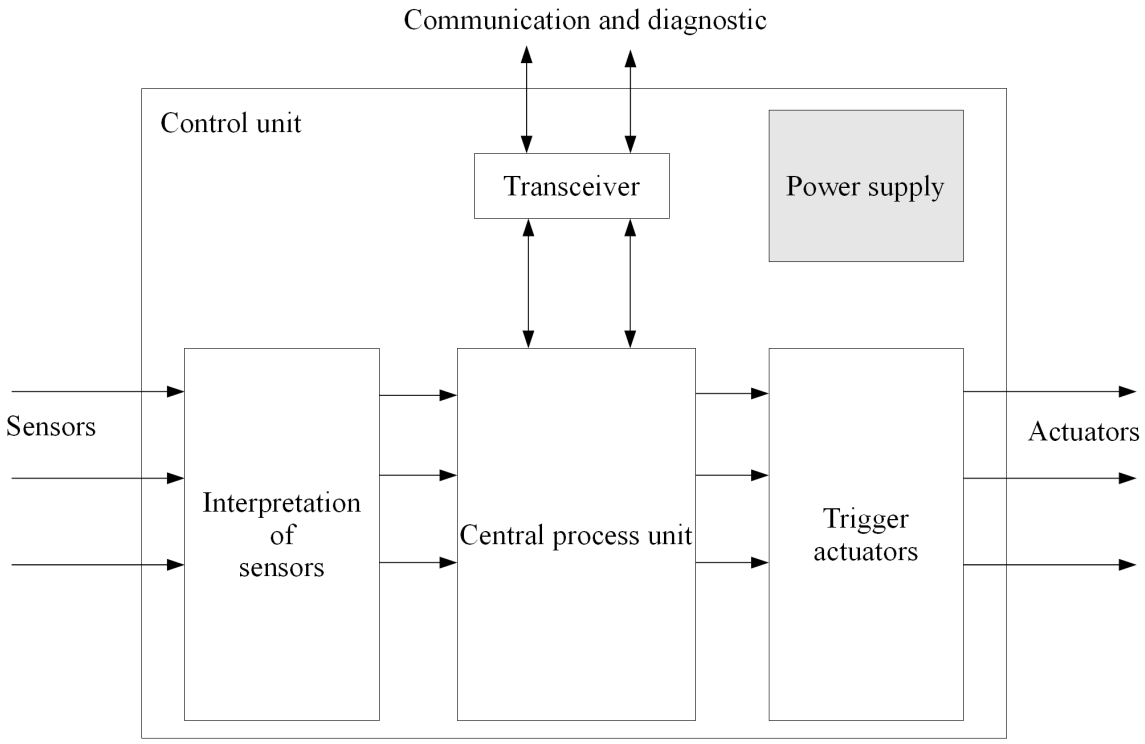


Figure 3.1: Control unit build up

A control unit is similar to a personal computer but has special requirements like an automatic reboot on a controller crash, further actions like a controlled shutdown of the whole system or an advanced digital signal processor (DSP). Control units undertake measurement, control and monitoring tasks. Therefore auxiliary components like a status monitoring system are installed, shown in figure 3.2. Additional components are the supply voltage (V), the oscillator (f), memories and the bus connections between memory and CPU which are integrated in a personal computer as well. RAM and EEPROM are used as memories connected over a serial bus to the CPU, (Borgeest, 2008).

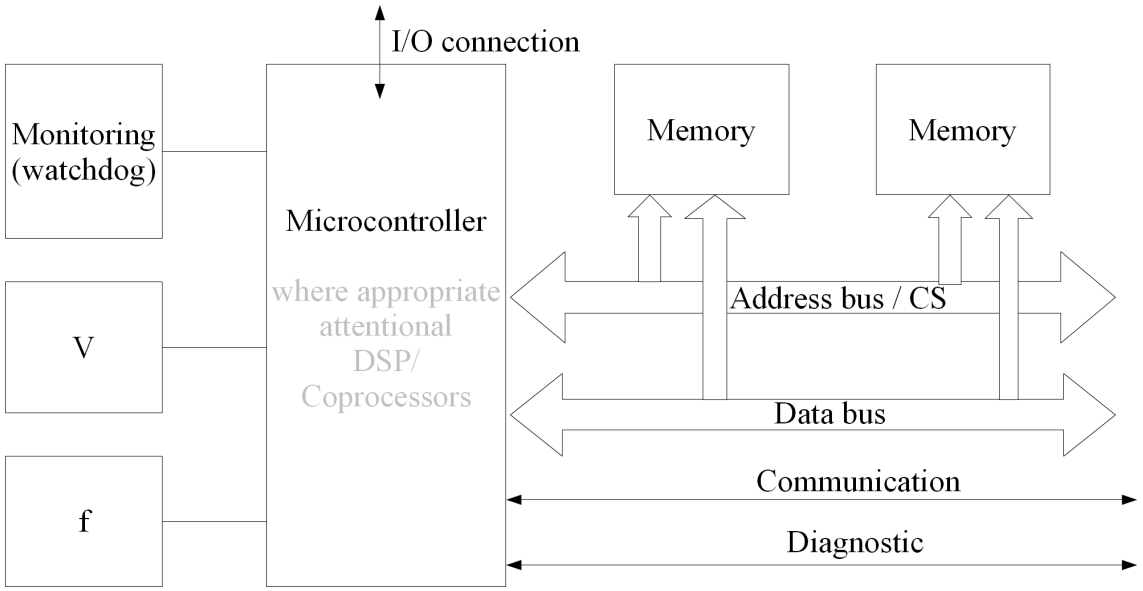


Figure 3.2: Additional components of a control unit

3.1.1. The microcontroller

The difference between a microcontroller and the processor of a customer computer are the added functional units, which are required for control applications. Examples are an integrated analogue digital converter or pulse width modulated outputs. Also the digital signal processing is optimized. Therefore special functions, like for multimedia purposes are missing.

A criterion for the microcontroller performance is the indication of bit numbers which can be processed parallel in a single operation (clock cycle). An example for the bit number is the used microcontroller AT90CAN128 who has an 8 bit internal bus system. Another criterion is how many clock cycles are needed to process a single instruction. With exception of complex instructions, like the mathematical division, modern microcontroller can process one instruction within one clock cycle. That means the microcontroller speed is proportional to the clock cycle. Well known microcontroller manufacturers for automotive applications are Atmel, Fujitsu, Infinion, Microchip or Freescale.

3.1.2. Memories

Memories are differentiated in volatile and non-volatile memories. Volatile memories loose the stored data after switching off the supply voltage whilst non-volatile memories keep the data.

A volatile memory is the random access memory RAM. The RAM is differentiated in SRAM which stores the data with flip-flops and DRAM which stores the data in little capacitors. The capacitors capacity is very limited to femto farad on the circuits. That means the capacitors need to be recharged in a rhythm of milliseconds. Therefore a refresh controller is needed which is a disadvantage of the DRAM. For this reason the SRAM technique in microcontroller applications is used.

The software (algorithm) and characteristics are stored in the non-volatile memory. Therefore personal computers using the hard drive which stores the data magnetically. The data from the hard drive is loaded into the RAM. A hard drive is not used in an embedded system due to the size and non shock resistance of a hard drive.

For this reason embedded systems use fixed wires. A fixed connection to ground or supply voltage represents a logic “0” or “1”. Such a device is called read only memory ROM or mask ROM. The terminology “mask” has the origin in the integrated circuit fabrication. Some regions of the chip are masked off during the photolithography process. The MROM stores the data steady and can not be programmed by the car manufacturers. This method is only lucrative on a large number of items, due to the high development costs of a MROM.

Non-volatile memories which are programmed by the car manufacturer are called PROM. During the programming process microscopical little fuses in the semi conductor are destroyed to image the stored data. This procedure is irreversible and is called one time programmable OTP.

But during the development of embedded systems it is helpful to erase the ROM and reprogram it. Such a device is called EPROM. The programming takes place using floating gate transistors and a specific voltage. To erase the ROM ultraviolet radiation is used. Hence EPROMs have a quartz glass window in the microcontroller housing to

expose the chip. Unintentional erasing of the ROM can occur by gamma radiation.

Due to the intricateness and tediousness in the erasing process of an EPROM EEPROMs were developed. The microcontroller has not to be removed from the circuit and can be reprogrammed with the ISP or ICP interfaces, which is an advantage of the EEPROMs. EEPROMs with little store capacity are connected over a serial bus and not via the parallel bus to save costs and circuit space. That is why they are called serial EEPROMs. EEPROMs with a short programming time are called flash EEPROMs or briefly flash. The number of programming cycles is limited, (Borgeest, 2008). In the case of the AT90CAN128 to 10 000 write/erase cycles and therefore the EEPROM should not be used as a RAM device, (Barrett/Pack, 2008).

3.1.3. Monitoring system

Personal computer users have experience with a crashed computer system. An example is the freezing of a program or an application. The user can solve the problem by restarting the computer. But this approach is not applicable for embedded systems and especially not for safety relevant application in cars.

For this reason the controller is monitored and on occurrence of a failure a special action is implemented.

The easiest monitoring system is the watchdog. This is a device integrated in the controller and expects in certain time intervals an explicit signal of the microcontroller. If the watchdog does not receive the expected signal a fault is interpreted. Complex control units use application specific integrated circuits (ASICs) or even a second controller just for monitoring tasks.

The easiest reaction in the case of a fault is a reset. Complex control units use fault statistics and a stepped reaction. For example breaking the fuel supply or turn off of the complete system.

3.1.4. Generation of sensor data

Every control unit which has integrated sensors, like a hydraulic pressures sensor in the ABS system, acts as a measurement device. The sensors convert physical values into an electrical corresponding signal. Sometimes the electrical signal is in a region which is not useful and the signal must be transformed in another area. Also faulty signals must be detected and noisy signals should be filtered. Above all the signal must be digitalised to make it processable for the controller. Mostly the correlation between measured variable and sensor signal is not linear. That means the conversion factor is not constant and the controller needs to know the characteristics of the sensors to conclude from the measured signal to the actual physical value. In the following an abstract of installed sensors in cars with their applications is given:

- Temperature sensors: Measuring for example the temperature of the cooling water, engine oil, gear box oil or the engine inlet air. Thermal resistors are used to generate a voltage depending on the temperature. A distinction is drawn between thermistors where the resistance increases with rising temperature, called positive temperature coefficient PTC and thermistors where the resistance decreases with rising temperature, called negative temperature coefficient NTC. In the automotive sector NTC thermistors are used due to cost reasons. If the accuracy of the NTC is not sufficient more expansive PTC thermistors made of platinum are used. An example characteristic of a NTC thermistor is shown in figure 3.3, (Borgeest, 2008).

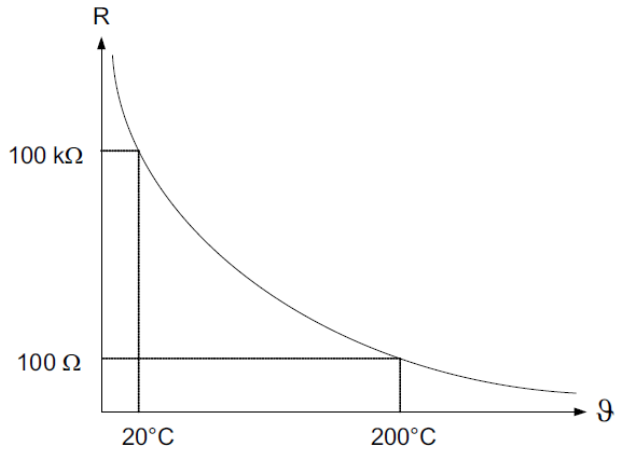


Figure 3.3: Characteristic of an NTC sensor

A resistance is not a directly measurable variable. Therefore the unknown resistance of the sensor across the power supply is series connected against a known resistor. After the voltage divider rule the sensor voltage can be calculated and indicates the measured temperature. The voltage can be processed in the controller. Figure 3.4 shows an example wiring to use the voltage divider rule, (Borgeest, 2008).

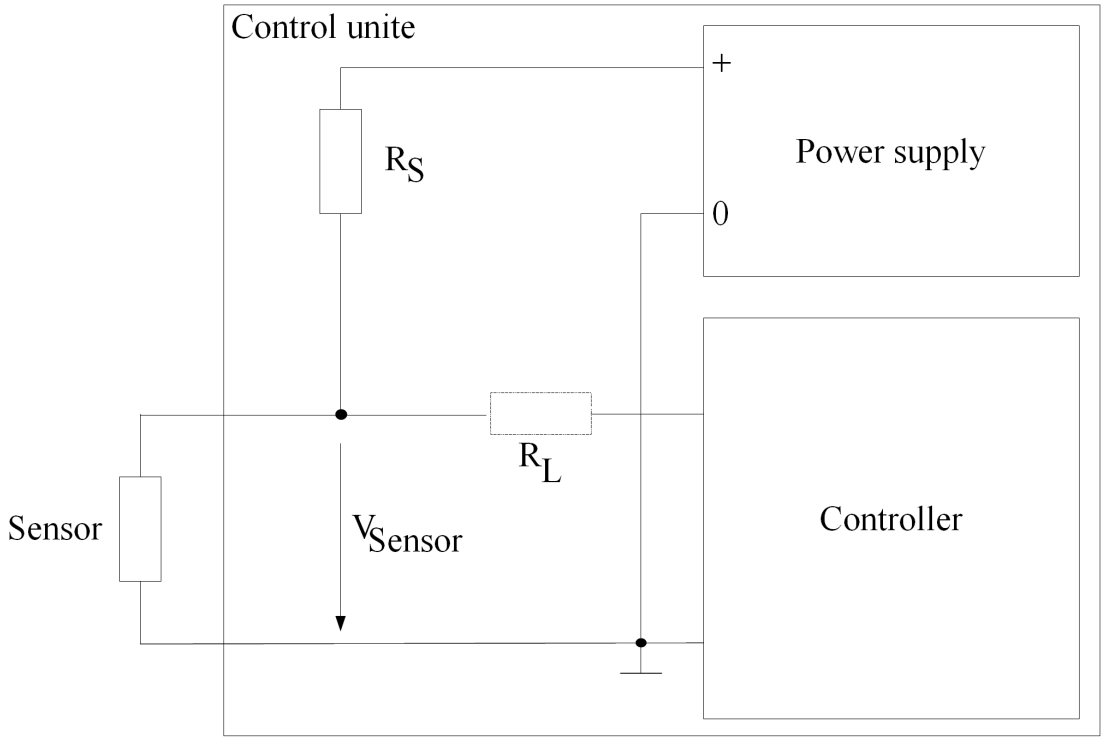


Figure 3.4: Wiring of a sensor with the voltage divider rule

The example shows a supply voltage provided by the control unit for the sensor over an in series connected resistor R_S. A common used voltage is 5V, which is also used for the microcontroller power supply. Also the signal has to be conditioned with filters. Normally capacitors are used which are connected between the signal wire and ground. It is useful to connect a load resistor R_L to decrease the load on the voltage divider, caused by the input impedance of the microcontroller.

Ceramic PTCs have a jumping characteristic curve and are only used for switching purposes, not for measuring, (Borgeest, 2008).

- Distance and angle sensors: Are used to estimate the position of an electrical actuator. Example applications are the angle of the acceleration pedal or the steering wheel. For distance, measurement potentiometers are mostly used, where a flexible wiper moves over a resistive element and grips some voltage, depending on the position of the polisher. Due to the abrasion, manufacturers passed on to more expansive contact free sensors. Contact free sensors using magnets, which are moved over a magnetic field. To detect the distance to another vehicle the radar technique or optical sensor are used.
- Vehicle speed sensors: Using the wheel speed sensors, which measuring indirectly the speed. The relative speed to other cars is measured with optical sensors and radar systems.
- Rotation speed sensors: Are used for example for the engine rpm. The rpm can only be measured with a magnetic sensors, because optical sensors are prone to pollution.
- Acceleration sensors: Are used for dynamic stability control systems, crash detection, anti theft protection and noise vibration harshness (NVH) related applications. Tilt sensors are measuring the acceleration of the gravity in a special direction and hence determine the tilt.
- Pressure sensors: Are used for the measurement of the gas pressure like in the atmospheric, in the turbo charger or in the tyres and also for fluid pressures used in the fuel injection process or in the braking system. The atmospheric pressure sensors have to measure a pressure in the area of 1 bar, while sensors for the injection pressure of the fuel have to measure a pressure till 2000 bar. Typical sensors consisting of a membrane made of silicium or metal. One side of the membrane is the measured pressure and on the second side a reference pressures. The bending of the membrane is measured by the change in the resistance.
- Moisture sensors: Are used to measure the air humidity inside the vehicle to avoid fogging of the window by heating or drying the air using the air conditioning system. This kind of sensors consists of capacitors with a porous dielectric which

changes the capacity with the absorption of humidity.

- Gas sensors: Are used especially for the exhaust gas treatment. An example is the oxygen sensor. Also the ventilation is controlled depending on the air quality inside the car (measuring the CO_2) and the fresh air (measuring CO_2 exhaust of the car in front), (Jurgen, 1999), (Turner, 2009).

Analogue Digital conversion

The output voltage of the sensor is the signal input for the microcontroller. The voltage has a defined range and needs to be converter for further processing. This is the task of the analogue to digital converter.

The continuous output voltage of the sensor is usually between 0V and 5V. This voltage is quantised in discrete values which is called quantization. The number of quantization levels determines the resolution of the system.

The discrete values over a range of analogue values are stored electronically in binary form. For example: A resolution of n = 10 bit for an A/D converter can encode different analogue input levels $N = 2^n = 2^{10} = 1024$, which equals the binary unsigned integer numbers 0x00 (decimal 0) till 0x3FF (decimal 1023) or from decimal -512 till +511 as signed integer. Table 3.1 clarifies the relation of hex values and decimal numbers in signed integer format.

Read hex code	Corresponding decimal value
0x1FF	511
0x1FE	510
...	...
0x001	1
0x000	0
0x3FF	-1
...	...
0x201	-511
0x200	-512

Table 3.1: Read hex code and corresponding decimal value

Figure 3.5 illustrates a 3 bit A/D converter. For the conversion a reference voltage V_{ref} is needed which is connected externally or generated by the microcontroller. Therefore the input voltage is not measured absolutely, but in relation to the reference voltage V_{rel} ($V_{in} - V_{ref}$). The figure 3.5 shows two different ways to quantise the measured relation and to allocate a binary number.

The method shown on the left of figure 3.5 is characterised as unsymmetrical, which is also called mid tread coding. For example an input voltage of 2.4/8 results in a 010 binary value, which is equal to 2 decimal. An input voltage of 2.6/8 results in 011 binary, which is equal to 3. Only when the relation voltage is equal to x.5/8 the binary value can be read in two different numbers. For example 2.5/8 is the relation voltage, the binary number can be 010 or 011.

The quantisation method shown in the right of figure 3.5 uses another interpretation of the binary values. For example the binary value 010 is read when V_{ref} is bigger than 2/8, (Borgeest, 2008).

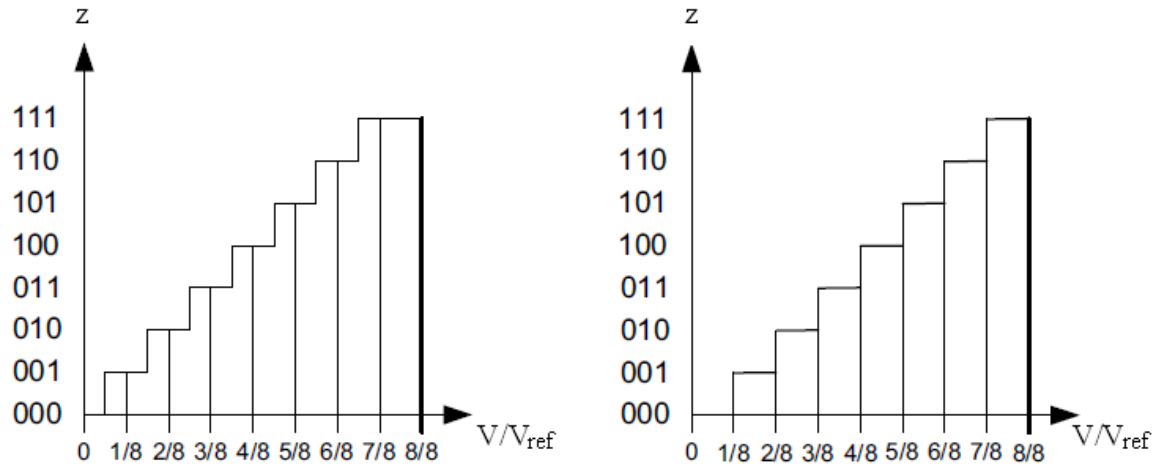


Figure 3.5: ADC interpretation of the voltage area in binary against V/Vref

A single pole reference voltage is applied when the minimal input voltage of the A/D converter is 0V related to ground. When a bipolar reference voltage is used and the minimal voltage differs from ground, the maximal reference voltage V_{ref+} as well as the minimal reference voltage V_{ref-} are indicated. An example input voltage of 5V against

ground and a resolution of 10 bit results in 1024 quantisation levels. Each level has a gauge of 4.883 mV. Feeding the minimal reference voltage (ground or V_{ref-}) on the input of the A/D converter produces a 0 (in binary as well as in decimal). The maximal reference voltage V_{ref+} on the input produces a 1023 decimal.

The input voltages and the sampling time are quantised. Commonly a measured value is sampled at fixed intervals, e.g. 10ms. Alternatively an event triggered sampling is also possible.

After starting an A/D conversion a specific time, depending on the converter type, is needed till the correct binary value is created and transmitted to the arithmetic logic unit. The controller sets a status bit (flag) or executes an interrupt at the end of a conversion. The following table 3.2 shows the main characteristics of the established A/D converter types. The letter n indicates the resolution in bits.

Type	Characteristic
SA Converter (Successive Approximation)	n conversion steps, while only n relation voltages are needed. **Main used converter type in automotive control units.**
∑Δ Converter (Sigma – Delta)	The technical implementation is to 90 % digital, including required the filters. Used especially in consumer electronics (e.g. entertainment systems).
Flash Converter	Fastest conversion method with only one conversion step. Very hardware extensive due to the requirement of 2^n trimmed resistors.
Dual Slope Converter	Very slow method. Using the integration principle with highest accuracy. Used for high precise measurement tools.

Table 3.2: A/D converter types

A constant input voltage is an important condition for a correct conversion to a digital value. This condition is satisfied by slow changing signals like temperature sensors. For fast changing signals like the output of acceleration sensors, the signal has to be held on a constant value for the conversion. Therefore a sample and hold device, which is normally included in the microcontroller, freezes the signal for a given amount of time.

3.1.5. Activating the actuators

Actuators can be differentiated if they are digital activated, which means on or off, or analogue activated, which means the current or voltage is variable to control the actuator. A second criterion of actuators is the electrical behaviour. Many actuators in cars are electrical described mainly by their resistance, conductivity or a combination of these two values. Another group are capacitive actuators and a special group are electric motors. The following table shows an overview of actuators in cars.

Actuator group	Digital (on/off)	Analogue (continuous value range)
Capacitive actuators	Sparking plug	Piezo injector
Ohm resistive actuators	Airbag Seat belt tensioner Headlights	Vehicle interior heating Vehicle interior lighting
Inductive actuators	Electro magnetic valves	Electro magnetic injectors Electro pneumatic valves
Electric motors	Starter Windscreen wiper Seat adjuster	Vehicle interior ventilation Electrical steering assistant

Table 3.3: Automotive actuators

Only a few actuators can be directly controlled by the microcontroller. Commonly the output signal from the microcontroller to the actuator has to be transmitted using a power semi conductor. For actuators controlled with a continuous voltage or current range the digital signal of the microcontroller has to be converted to a corresponding analogue signal and is transmitted by a power semi conductor, (Jurgen, 1999).

D/A Conversion

The D/A conversion depends on the digital output signal of the microcontroller.

- Is the output signal parallel, every wire of the output port indicates the electrical status of a single bit. This method is implemented in an extra complex D/A converter component. Due to the costs this solution is not used in the automotive sector.

- For a serial output signal no converters are existing. But this method is sometimes useful for transmitting the signal over the bus system to other control units. For the D/A conversion the data has to be parallelised.
- The third method is pulse width modulation (PWM). The controller output on one port is a square wave signal. The signal is divided in for example 255 equal time periods.
    - To represent the number 0, the signal has to be turned off for the whole period (T = 0).
    - To represent the number 255, the signal has to be turned on for the whole period (T = 1).
    - To represent the number 127 for example, the signal has to be turned on for a sampling period of T = 127/255, which is almost 0.5.
    - To represent a number bigger than 255, one period has to be divided in more then 255 areas.

  An advantage of this method is the very easy and cheap conversion of a digital signal in an analogue signal, (Wallentowitz/Reif, 2006).

3.2. The CAN bus

As described in chapter 1 the CAN bus was developed by Bosch and Intel in 1986. The first car produced in mass production fitted with the CAN bus was the Mercedes S class in 1992, (Hristu-Varsakelis/Levine, 2005). In 1993 the CAN bus was standardised in the ISO 11898 which consists of five parts:

- Part 1: Data link layer and physical signalling
- Part 2: High speed medium access unit
- Part 3: Low speed, fault tolerant, medium dependent interface
- Part 4: Time triggered communication
- Part 5: High speed medium access unit with low power mode

This means the standard defines the OSI Layers 1, 2 and 7 shown in figure 3.6, (Borgeest, 2008).

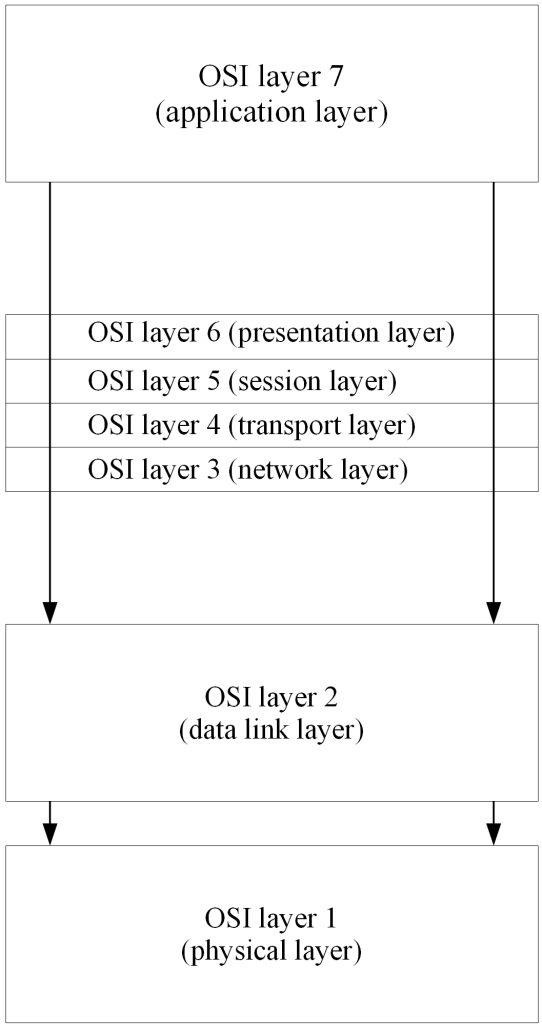


Figure 3.6: OSI layers

The OSI model is the basic principle for designing communication protocols and bus systems. The model consists of seven layers which are explained roughly as follows:

- Layer 1: Physical Layer

  It defines the electrical and physical specifications for the bus devices like voltage range, cable specifications or the adapters.

- Layer 2: Data Link Layer

  It is responsible for the communication between adjacent network notes.

- Layer 3: Network Layer

  It provides the procedural and functional logic of transferring data sequences from a source to a destination over several networks.

- Layer 4: Transport Layer

  It controls the data flow and is responsible for the end to end connection.

- Layer 5: Session Layer

  It provides the communication between different systems.

- Layer 6: Presentation Layer

  It presents the data in a system independent format. A second task is the encryption and decryption of the data.

- Layer 7: Application Layer

  It is the access to the network for applications, (Zimmermann, 1980).

3.2.1. Physical Layer of the CAN bus

The physical and the data link layer are available as integrated circuits with the differentiation of CAN transceivers for high speed and low speed systems. In the following the circuits of the high speed and low speed CAN transceiver is explained in more detail.

The figure 3.7 shows the principle structure of a CAN interface. The CAN controller manages the data stream between the ECU and the CAN bus, (Wallentowitz/Reif, 2006).

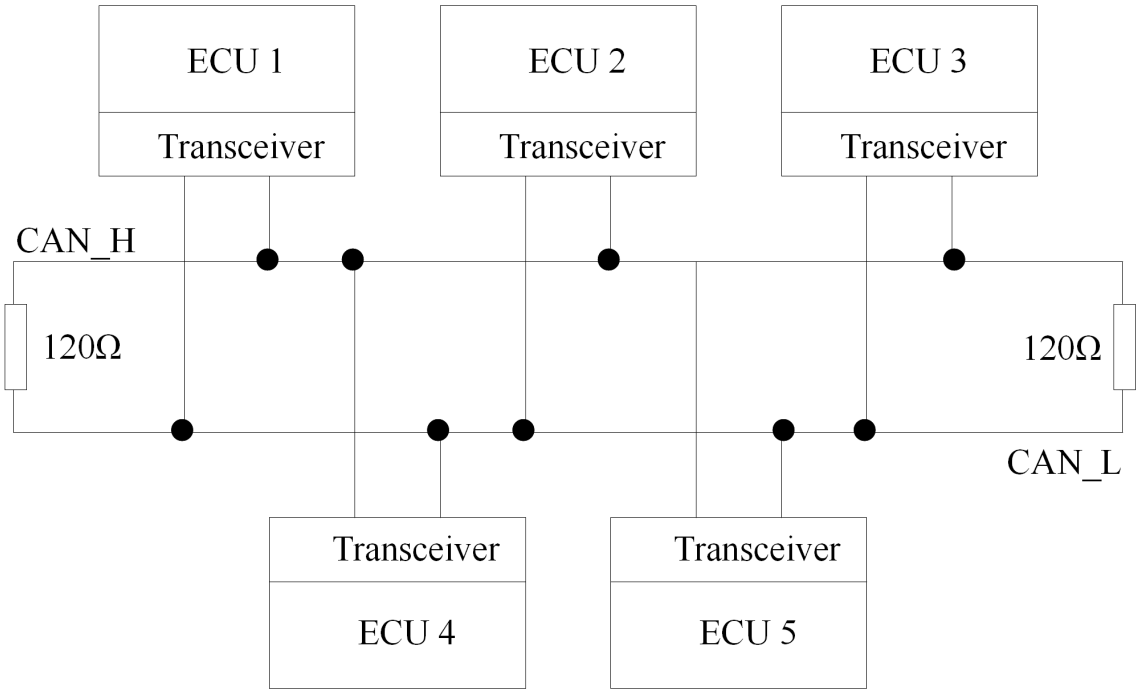


Figure 3.7: Wiring of the CAN bus

The high speed CAN

The specification allows a data rate up to 1 Mbit/s but in common application like the wiring of the powertrain a data rate of 500kBit/s is enforced. For the signal transmission a twisted pair of cable is used. The CAN protocol uses the non return zero code for bit coding and defines a dominant and recessive bus level for the arbitration after CSMA/CA. Figure 3.8 shows the nominal potential and the allocation for the high speed CAN.

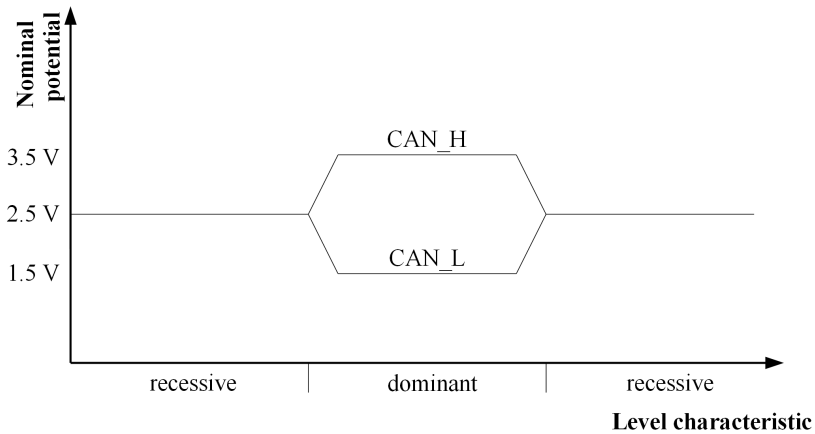


Figure 3.8: Nominal potential of the high speed CAN

The low speed CAN

The communications between the control units of the comfort system like the air conditioning or electrical seats are independent from the high speed CAN system. The data rate is limited to 125kBit/s and is therefore classified as low speed CAN or CAN-B. The numbers of control units in one low speed CAN network is limited to 32. The lower data rate enables another fault detection mechanism which means the low speed CAN is fault tolerant to electrical short circuit and adjournment between the data wires CAN_H and CAN_L. The figure 3.9 shows the nominal potential of the fault tolerant low speed CAN. Compared to the high speed CAN in figure 3.8 the difference of potential is much higher between the dominant and recessive bit. Therefore it is possible to run the low speed CAN on a single wire. The transceiver is able to detect an adjournment in the data wires CAN_H or CAN_L, a short circuit between CAN_H and CAN_L, a short circuit between ground and one of the data wires or a short circuit between supply voltage and the data wires. In that case the transceiver switches automatically the mode of operation which means the faulty data wire will be turned off and only the other wire is used for the data transmission.

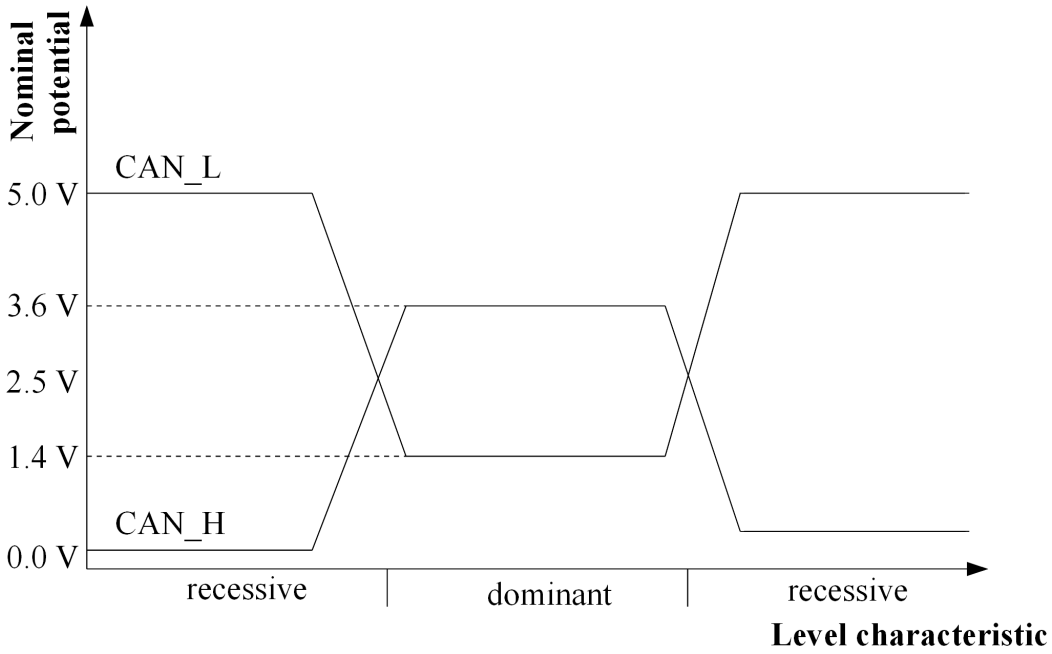


Figure 3.9: Nominal potential of the low speed CAN

3.2.2. Data Link Layer

Every control unit has the same priority in the CAN bus and the communication is event triggered. That means the CAN bus is not deterministic unlike all event triggered bus systems. This kind of communication is called multi master principle. As an example: An ECU wants to send data to another bus participant. Therefore the ECU gives its CAN controller the task to set up the communication. The CAN controller sends the message when the bus is not used and when it is winning the arbitration. That means every connected control unit to the bus has no physical address. Instead every message has a specific and explicit identifier. The control units can recognise the content of the message by the identifier.

Also the data link layer specifies the structure of a CAN data frame. The data frame begins with the CAN identifier (CAN-ID) with the information of the data and the priority of the data frame in the arbitration. The arbitration is used to control the bus access.

Sending a CAN message

The next figure shows the flow chart for the arbitration process, (Binder, 2008).

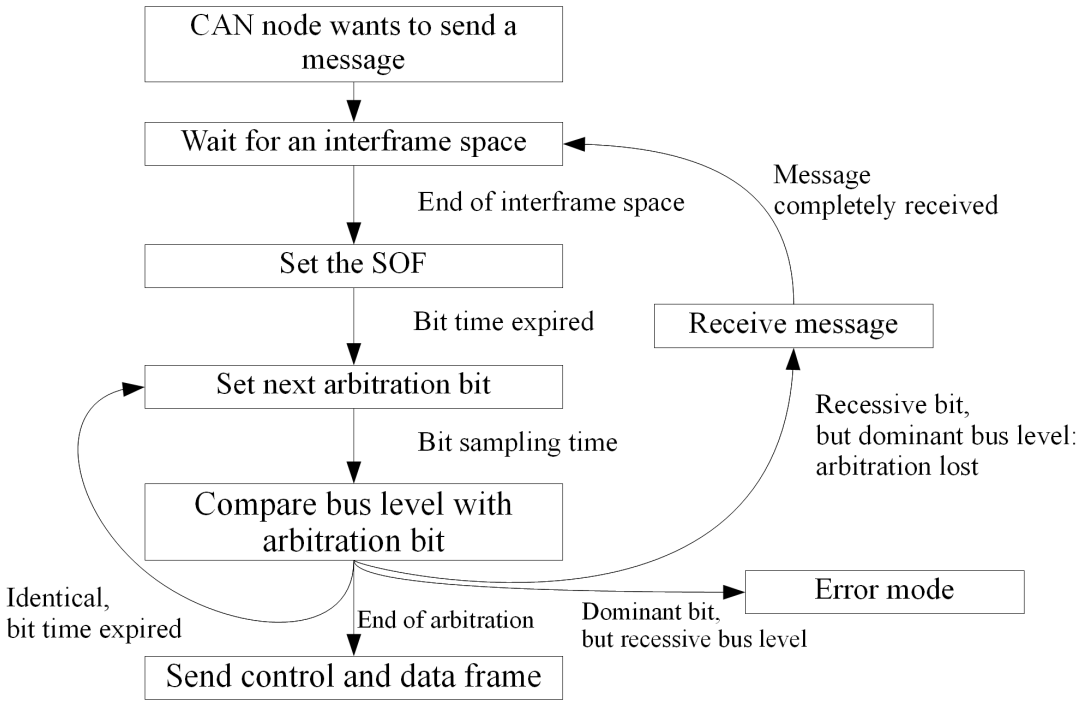


Figure 3.10: Flow diagram of the arbitration process

The following case is given in figure 3.11: Two CAN controllers want to send a message with the identifier CAN-ID A and CAN-ID B at the time after the principle of CSMA/CA.

The bus level is recessive in bus idle mode and the transmission starts with the broadcast of the start of frame bit (SOF) with a dominant level. All control units in the CAN network are synchronised on a falling edge of the SOF bit. On the bit by bit arbitration the transmitter compares the bus level with the own sent bit, which is recessive or dominant. The arbitration is continued till the sent bit level and the received bit level are matched. The transmitter receives a dominant bit while it was sending a recessive bit, the arbitration is lost and the control unit stops the transmission. The CAN controller with the CAN-ID A looses the arbitration on the seventh bit after the SOF.

In the example the two CAN controller send at the same time. The bus level stays recessive if no controller sends a dominant bit. The bus level changes to dominant if one or more controller send a dominant bit. The controllers compare the own sent bit with the bus level. After the seventh bit the CAN controller with the CAN-ID A sends a recessive bit while the controller with the CAN-ID B sends a dominant bit. The controller with the CAN-ID A compares the own sent bit with the received bus level and recognizes a variation. That means it looses the arbitration and stops sending messages. Now the controller with the CAN-ID B can start sending a message, (Borgeest, 2008).

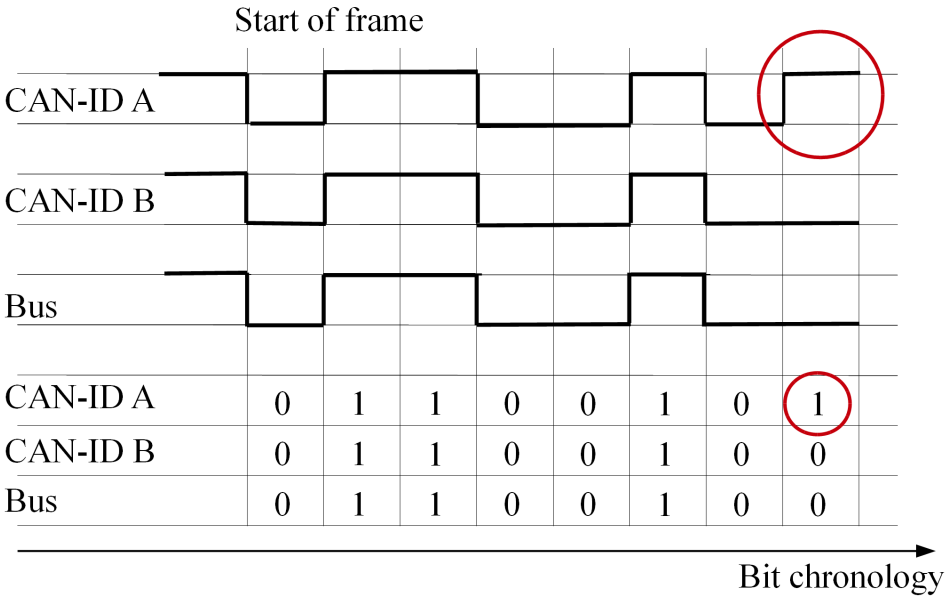


Figure 3.11: Example of the arbitration

Receiving a CAN message

Control units in the CAN network receive only relevant messages, because a programmable acceptance filter is implemented which checks the CAN-IDs. The CAN-ID indicates the content of the message as well as the priority used in the arbitration. Also it is possible to control partly the latency time with the identifiers. But the only message with a guaranteed latency time is the message with the highest priority. The identifier with the lowest binary number has the highest priority. The identifier is in standard format 11 bit long (CAN 2.0A) or 29 bit in extend format (CAN 2.0B).

Structure of CAN data frames in standard format

There are four different CAN data frames existing:

- Data frame;
- Remote frame;
- Error frame;
- Overload Frame;

Data Frame

The data frame is used to send data or indicate events. Figure 3.12 shows the structure of a data frame, (Wallentowitz/Reif, 2006).

1	11 + 1		6	0...64	15 +1		2	7	3...
	Arbitration		Control	Data	CRC		ACK	EOF	Interframe space
SOF	Identifier	RTR	IDE r1 DLC		CRC	CRC delimiter	ACK Slot ACK delimiter	End of frame	

Figure 3.12: Structure of a CAN data frame

Start of frame: In case of no control unit is transmitting a message, the bus is in recessive mode. A data frame begins with a single, dominant bit which is the SOF. The transmitter and receiver of the message synchronise on the falling edge.

Arbitration field: The arbitration field is twelve bits long and consists of the CAN identifier (eleven bits) and a single RTR bit. The RTR bit determines if the message is a data frame or a remote frame. If the RTR bit is dominant, the message is a data frame and if the RTR bit is recessive the message is a remote frame.

Control field: The control field consists of six bits. It contains an identifier extension bit (IDE), a reserved bit for future developments and four bits for the number of data bytes in the data field, called data the length code (DLC). The IDE bit shows if the CAN frame is in standard or extended format. A dominant IDE bit means CAN standard format (eleven bit CAN-ID) and a recessive IDE bit means CAN extended format (29 bit).

It is allowed to send data in a CAN network in standard format as well as in extended format at the same time. A message in extended format with the same first eleven bits (called base identifier) of the identifier against a message in standard format means the message in extended format will lose the arbitration.

The DLC consists of the four bits (DLC0 till DLC3), which means 16 different conditions can be represented. But the maximal number of data bits is limited to eight byte. In table 3.4 the data length code with the number of bytes is illustrated.

DLC3	DLC2	DLC1	DLC0	Bytes of data
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8

Table 3.4: Indication of bytes by the data length code

Data field: The actual data of the message is transmitted in the data field which is zero to eight bytes long. The data transmission starts with the most significant bit.

CRC field: The CRC field consists of a 15 bit long CRC check sum and the CRC delimiter which indicates the end with a recessive bit.

ACK field: The acknowledge field consists of the single ACK slot bit and a single recessive ACK delimiter bit. The transmitter sends a recessive ACK slot bit and the receiver will change this bit to dominant in case of a successful and an error free data transmission.

End of frame: The end of frame field consists of seven recessive bits. After the end of frame follows the interframe space which is a recessive bit. The interframe space ends when no control unit sends a SOF.

Remote Frame

The remote frame is used to request special messages, labelled by the identifier. Figure 3.13 shows the layout of the remote frame, (Wallentowitz/Reif, 2006).

1	11 + 1		6	15 +1		2	7	3...
	Arbitration		Control	CRC		ACK	EOF	Interframe space
SOF	Identifier	RTR	IDE r1 DLC	CRC	CRC delimiter	ACK Slot ACK delimiter	End of frame	

The body of a remote frame is almost identical to a data frame. Only two characteristics are different:

- The RTR bit is recessive.
- The data field is empty.

The DLC of the remote frame must be equal to the DLC of the requested data frame. The CAN-ID of the remote frame and the CAN-ID of the requested data frame are the same.

In case of a control unit with a CAN-ID and a dominant RTR, which means data frame, is sending a message and a second control unit is sending a message with the same CAN-ID but with a recessive RTR bit at the same time, which means the control unit with the dominant RTR is winning the arbitration. This means data frames have a higher priority than remote frames, which is sensible, because remote frames are requesting data which can actually be sent by the data source.

Interframe Space

Data and remote frames are separated by the interframe space. The interframe space consists of an intermission field and an arbitrarily bus idle. The intermission field has three succeeding, recessive bits. The bus idle has recessive bits as well and arises when no CAN node is sending a dominant bit. In the intermission field no CAN node is allowed to send a data or remote frame. With the three bit intermission field, the seven EOF bits and the recessive ACK delimiter are eleven recessive bits on the bus in a sequence between two messages. After the sequence the bus is free and can be used for a new transmission starting with a SOF bit.

Error frame

When a CAN controller detects a disturbance it stops a running data transmission by sending an error frame. The error frame has an error flag and an eight bit error delimiter. The error flag has six dominant bits and overwrites all other bits on the bus. Thus breaks the bit stuffing rule on purpose. The bit stuffing rule is explained later in this thesis, chapter 3.2.3.

Breaking the bit stuffing rule causes new error flags of other connected control units, because they are detecting an error on the bus (six dominant bits in a sequence). The outcome is an overlap of dominant bits on the bus and the length of the error flag varies between six and twelve bits.

The second field of the error frame is the error delimiter which consists of eight recessive bits. These bits are sent after the end of the error flag. After the error flag the control unit sends a single recessive bit and waits till the bus becomes recessive. When the bus is recessive the control unit sends the last seven recessive bits of the delimiter.

Error flags secure data consistency within the system. After detecting a fault by a single CAN controller, the controller sends an error flag which shows all other CAN controllers an invalid message. Due to the characteristic of the bus system a defect control unit can block the bus by permanently sending error frames. To avoid this effect the CAN protocol defines three different fault statues:

- Error active;
- Error passive;
- Bus off;

Every CAN node has a transmit error counter (TEC) and a receive error counter (REC). The control units increment and decrement the counter after defined rules. Depending on the counter, the control unit changes the fault statues from error active over error passive to bus off or reverse which is shown in figure 3.14, (Borgeest, 2008).

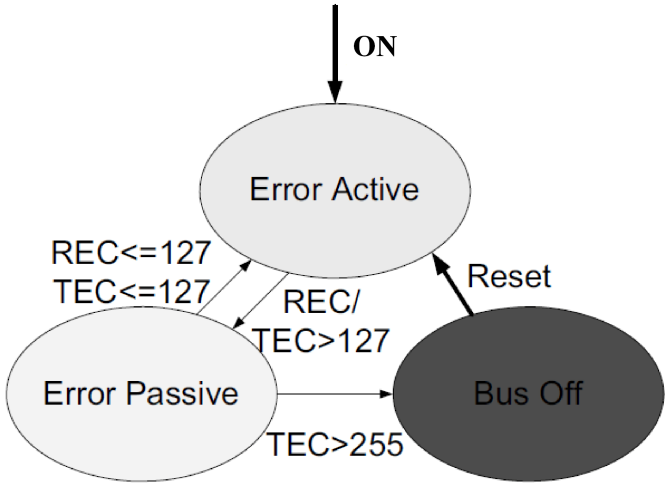


Figure 3.13: CAN bus error model

An error active CAN controller can notify detected faults by sending error frames. Exceeds one of the two fault counters (REC/TEC) the value 127, the controller changes the status to error passive. In case of both fault counters having a value smaller than 128 the controller goes back to fault active status.

A controller in fault passive status sends a sequence of six recessive bits in case of fault detection. This means the controller is not able to overwrite messages which are received error free from other control units.

A CAN controller changes the status from error passive to bus off when the TEC is greater than 255. In this case the controller is completely decoupled to the bus system. Some controller can still receive messages in this mode, depending on their implementation.

After a reset all controller are in error active status. Only controllers in bus off status stay in their mode till they have received successfully 128 x 11 recessive bits. Then they are allowed to change the status to error active, which secures that no defect controller is blocking the bus after a reset, (Paret, 2005).

Overload frames

An overload exists when a bus user is not ready for receiving data or when a CAN controller recognises a dominant bit in the interframe space. A bus user for example can be busy with processing data and therefore it is not able to receive any more data. Then the bus user begins to write the first bit of the intermission field and sends an overload frame. The overload frame has six dominant overload flag bits and the overload delimiter.

The dominant bits of the overload flag are destroying the interframe space format. All other CAN nodes are expecting no dominant bits in the interframe space and so they send an overload frame. The outcome is an overload flag overlap. After the transmission of an overload flag the CAN node waits for an edge of a recessive bit. The edge shows the end of the overlapped overload flag. Now the CAN controllers send at the same time further recessive bits on the bus. The outcome is a sequence of eight recessive bits following the overload flag, which is called the overload delimiter. The overload frame causes no repeating of previous transmitted data and remote frames.

3.2.3. Fault detection methods of a faulty communication

The transmission of faulty data and remote frames can be stopped during the transmission process by sending an error frame. This assures data consistency within the system. The recovery time of the whole bus system after fault detection is quicker than 30 bit times.

The time duration for sending a bit depends on the data rate.

The CAN protocol has several different fault detection methods like CRC, message frame check, acknowledge, monitoring and bit stuffing.

CRC check: Data and remote frames are equipped with a checksum of the sending unit. The SOF bit, the arbitration field, the control field and the data field are considered as polynomial. The polynomial is divided by a generator polynomial with a modulo 2 division. The division rest is the CRC sequence. The receivers of the message calculate themselve a CRC checksum. This checksum is compared with the received checksum. On a faulty transmission the same CRC sequence occurs.

Message frame check: The length and structure of the frame is analysed during the message frame check process.

Acknowledge: The receivers of the message writing a dominant bit in the ACK slot which confirms a successful transmission.

Monitoring: All connected CAN nodes in the bus system are monitoring the bus level. In case of non conformance of the sent level with the received bus level a bit error occurred.

Bit stuffing: The signal level is constant during an entire bit time by the non return zero (NRZ) coding. The post synchronisation of the CAN nodes take place after the SOF using rising and falling edges between different bits. In case of a sequence of identical bits it is possible to have synchronisation problems without these edges. The transmitter inserts after five succeeding, identical bits a complementary bit to avoid synchronisation problems. The complementary bit is called a stuff bit. The stuff bit is also insert even when already after five succeeding identical bits a stuff bit would follow. The bit stuffing rule is applied in data and remote frames and begins with the SOF and ends before the CRC delimiter. For error and overload frames the bit stuffing mechanism is not used. The receiver of the messages applies the same rule and removes the stuff bits in the data stream. A bit stuffing error occurs when a receiver detects more then five succeeding, identical bits in the data stream, (Zimmermann/Schmidgall, 2007).

3.2.4. TTCAN

The event triggered communication causes a non predictable high latency time for messages with low priorities. That happens especially on heavy bus loads and faulty messages (e.g. through external noise) which means the data transmission must be repeated fairly often. Thus means the bus is not suitable for real time applications. To ensure real time ability in an event triggered CAN system 80% of the available bandwidth must be reserved for peak bus loads. Especially for safety relevant functions the latency time must be predictable. In all operating modes the transmission of safety relevant messages with a defined latency time must be secured, as well as on maximal bus load.

The ISO 11898-4 specifies the TTCAN protocol on the session layer of the OSI model to synchronise the CAN nodes for transmitting messages periodically at defined times. Safety relevant functions also require an increased fault tolerance (e.g. redundancy) and a higher data transfer rate. Especially the limited data rate of 1 MBit/s stopped the integration of TTCAN in cars for safety relevant functions, (Zimmermann/Schmidgall, 2007), (Navet/Simonot-Lion, 2009).

Chapter 4

The Development of a New Diagnostic Approach

A control unit consists of three main tasks. The main tasks are to control a process, provide diagnostic functions and a communication interface. The tasks of controlling a process and the communication interface is extensively explained in chapter 3.

The diagnostic functions include the self diagnosis of the control unit. In general the inputs and outputs of the control unit, the control function and the communication interfaces are monitored. In some cases it is required to check the control loop with defined conditions.

This chapter describes the communication between a tester and the control unit, which only can be initiated by the tester. The tester is a diagnostic device which requests information from the control units or a control unit in function of a gateway. The gateway control unit acts partly as an onboard tester and provides prefiltered and conditioned information for the external test device which simplifies the localisation of the fault cause.

4.1. History of diagnostic protocols

In Europe manufactured vehicles use the keyword 2000 protocol KWP 2000 for the diagnostic communication. In 1989 it was standardised in the ISO 9141 (Road Vehicles – Diagnostic systems) which defines the electrical properties, the mode of bit transferring and the communication initialisation process between test device and control unit. During the initialisation the devices are exchanging the keyword, which defines the used data protocol. The data protocol and the allowed values for the keyword were not defined in the specification and therefore several different manufacturer depending solutions are applied for the connections and connectors.

In the beginnings of the 1990s the California Air Resource Board CARB suggested a regulation to monitor emission relevant components of the car. Guidelines were made

regarding the identification, displaying and storage of an error while the vehicle is in operation. Also a diagnostic interface was claimed to check emission relevant information with a scan tool by the police, garages and agencies. The American manufacturers used the SAJ 1850 protocol while European manufacturers applied the ISO 9141 interface. The ISO 9141 was adjusted to full fill the OBD requirements and became to the ISO 9141-2 also known as ISO 9141-CARB. During the mid 1990s the European Union adopted the American regulations and modified them. In 1998 the ISO 14230 was specified under the term key word protocol 2000.

The ISO 14229 generalises the established KWP 2000 diagnostic principles to make them independent of the subjacent real bus protocols. The milestones of international standardised protocols are shown in the following table and figure 4.1:

Year	Norm	Title
1989	ISO 9141	Road vehicles – Diagnostic Systems Requirements for Interchange of Digital Information
1996	ISO 9141 CARB	CARB requirements
1998	ISO 14230	Diagnostic systems
2003	ISO 15031	Communication between vehicle and external equipment for emission related diagnostics
2004	ISO 15765	Diagnostics on CAN
2004	ISO 14229	Unified Diagnostic Services UDS

Table 4.1: Standardisation of diagnostic protocols

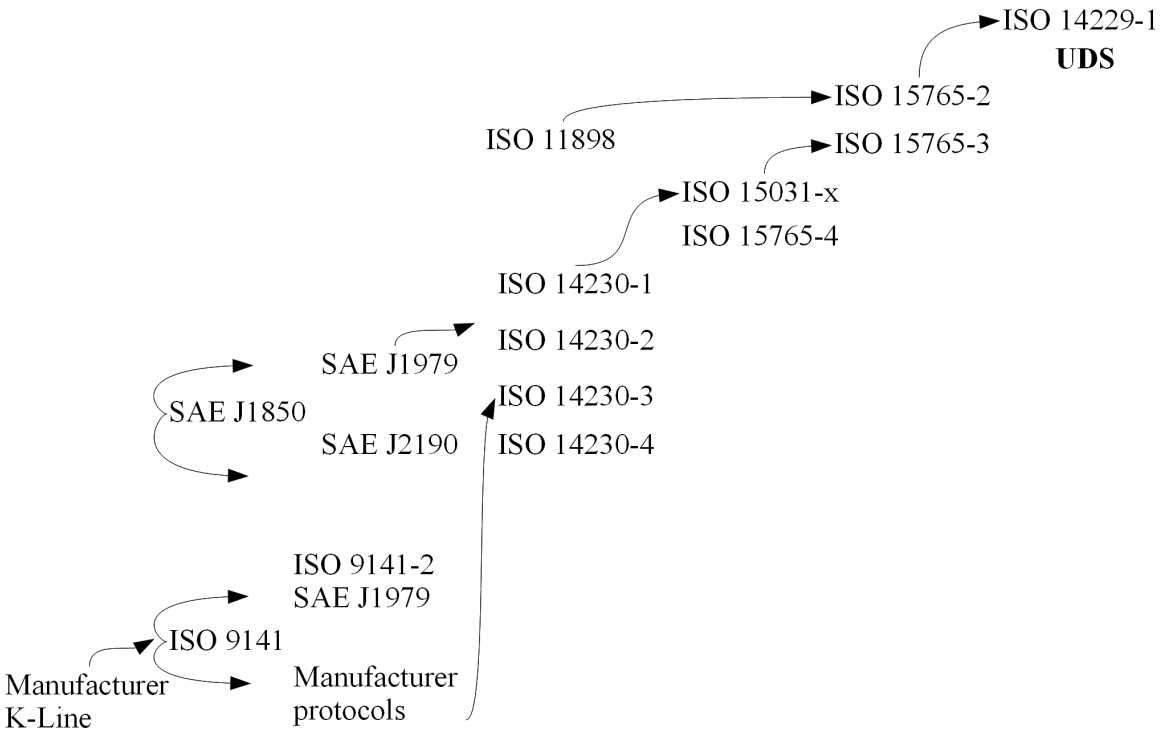


Figure 4.1: The development of automotive diagnostic protocols

The most used diagnostic protocol in European vehicles is the KWP 2000 protocol which was first realised with K-Line and later with the CAN bus. The KWP 2000 application layer is standardised in the ISO 14230 and is compatible with the CAN application layer which is standardised in the ISO 15765, (Wallentowitz/Reif, 2006).

4.2. Current diagnostic approaches

4.2.1. The K-Line and KWP 2000

Physical Layer

The K-Line is a bidirectional one wire bus. It is also possible to have a second unidirectional wire, called the L-Line. The L-Line is only used for the initialisation of the communication. The diagnostic tool is either directly connected to the vehicle bus system or over a gateway. The gateway is normally used when the internal vehicle bus system is not based on the K-Line. Figure 4.2 shows the K-Line topology,

(Zimmermann/Schmidgall, 2007).

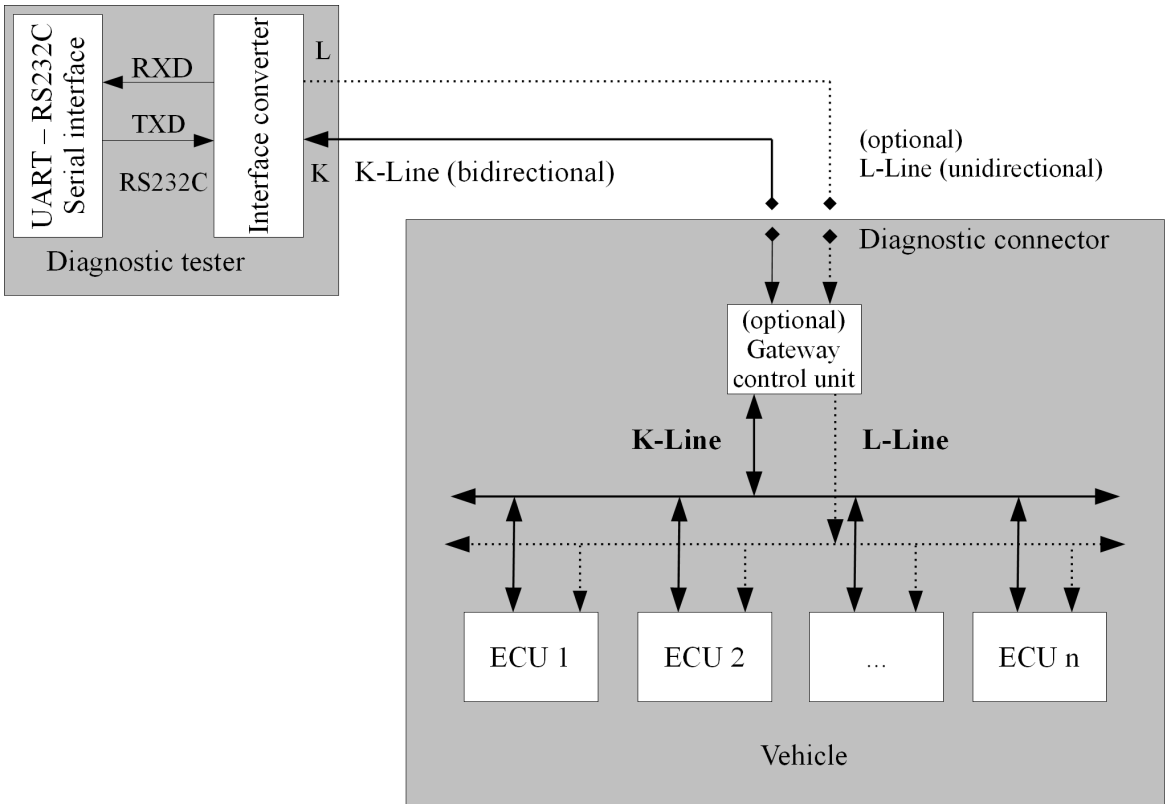


Figure 4.2: The K-Line topology

The bit transmission is UART compatible and is carried out character by character with one start bit, eight data bits and one stop bit. The baud rate is set by the control unit and is between 1.2 kbit/s and 10.4 kbit/s. Emission relevant control units must have a fixed baud rate of 10.4 kbit/s.

Data Link Layer

All the communication is initiated by the testing device with a diagnostic request to the control unit. The application layer indicates a diagnostic session for the control unit. The response of the control unit is sent back to the tester. The tester receives the confirmation over its application layer. The standard defines the control unit as server and the tester as client. The server client principle and the initiation of the communication is shown in figure 4.3. The test device is the master in the communication and the control unit the client (Zimmermann/Schmidgall, 2007).

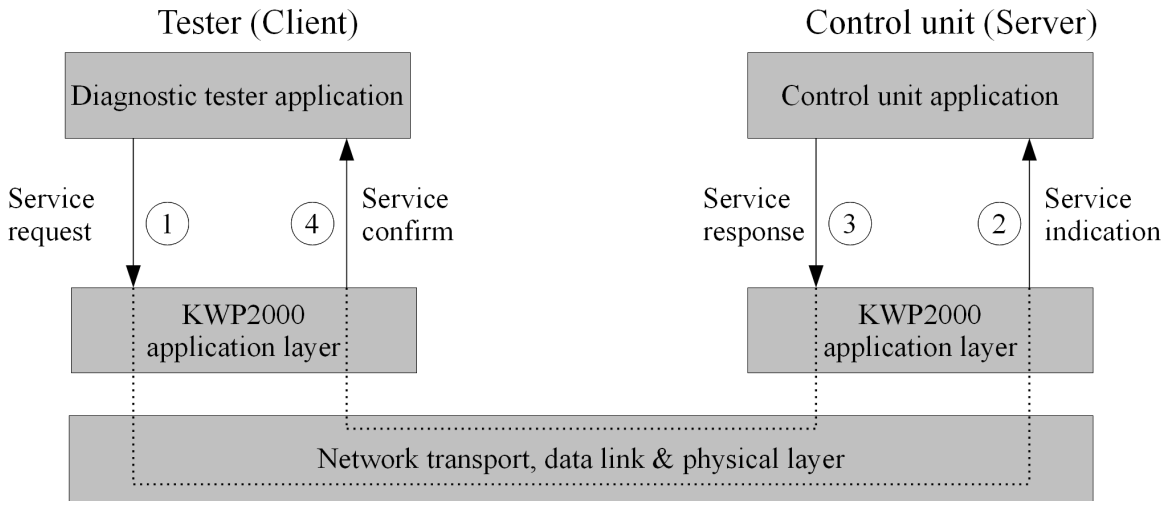


Figure 4.3: The server client structure and the initialisation of a diagnostic session

A diagnostic session is carried out in three phases:

- Initialisation;
- Data exchange;
- Connection termination;

For the initialisation the ISO14230 standard allows two methods, the fast initialisation which is not standardised yet and the defined 5 Baud initialisation.

The fast initialisation can only be applied with control units with a fixed baud rate of 10.4 kbit/s. The initialisation is carried out as follows:

- The K-Line and the L-Line are in idle mode (high) after switching on or a connection termination for at least 300ms.
- The diagnostic tool carries out a wake up pattern. That means the tester sets K- and L-Line at the same time to low for 25ms and afterwards for 25ms again to high.
- The further communication takes place only on the K-Line and the L-Line stays high.
- The diagnostic tool sends a start communication service request to the desired control unit with its address.

- The addressed control unit answers within 50ms with a start communication service response, which includes the keyword.

The fast initialisation process takes circa 100ms and is shown in figure 4.4, (Zimmermann/Schmidgall, 2007).

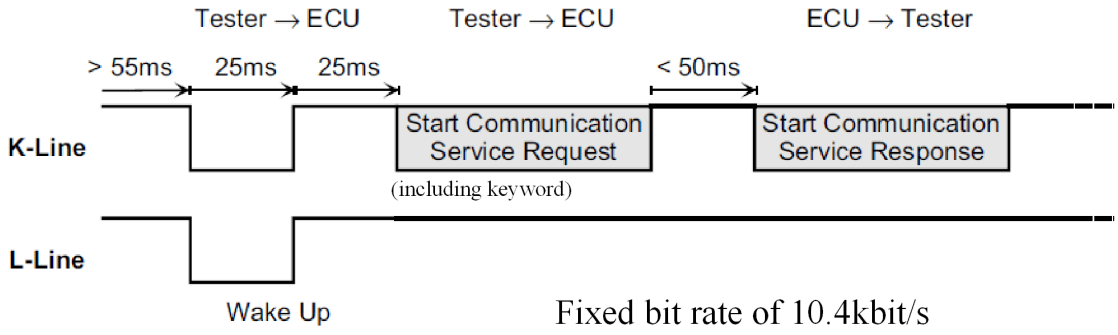


Figure 4.4: KWP 2000 fast initialisation

When another baud rate as 10.4kbit/s is required for the diagnostic communication the 5 baud initialisation is applied:

- The K- and L-Line are in idle mode for at leas 300ms.
- The diagnostic tool sends an eight bit long address word to the desired control unit at the same time on the K- and L-Line with a bit rate of 5 bit/s.
- The further communication only takes place on the K-Line and the L-Line stays on high level.
- The addressed control unit answers within 300ms by sending the synchronisation byte 55h. After the control unit sends the bytes of the keyword each with a gap of maximal 20ms. The control unit sends the data with its own, fixed bit rate between 1.2 kbit/s and 10.4 kbit/s.
- The test device measures the duration to receive the bytes sent by the control unit. The measured time indicates the test tool the used bit rate of the control unit and switches to the same bit rate and sends the second byte, the most significant byte within 20ms back as an echo signal.

- The control unit establishes the connection by sending the inverted address as echo.

The 5 baud initialisation process takes circa 2.5sec and is shown in figure 4.5, (Zimmermann/Schmidgall, 2007).

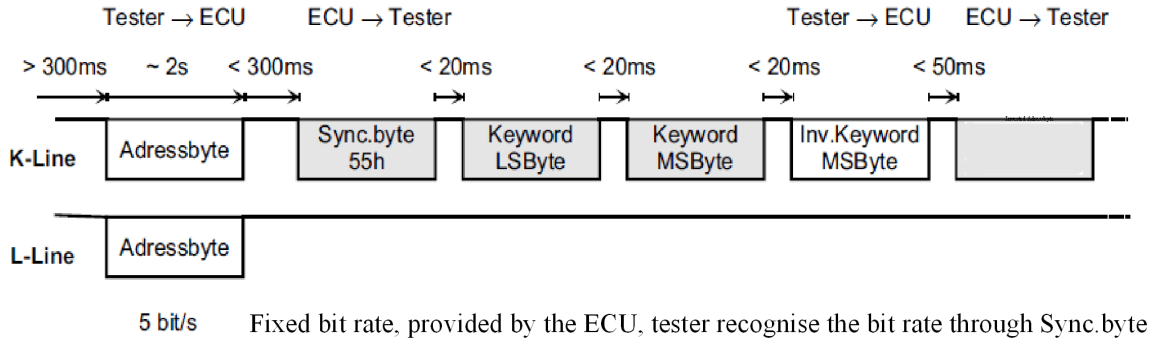


Figure 4.5: The KWP 2000 5 baud initialisation

The data exchange: The transmitted messages have the format illustrated in figure 4.6, (Zimmermann/Schmidgall, 2007).

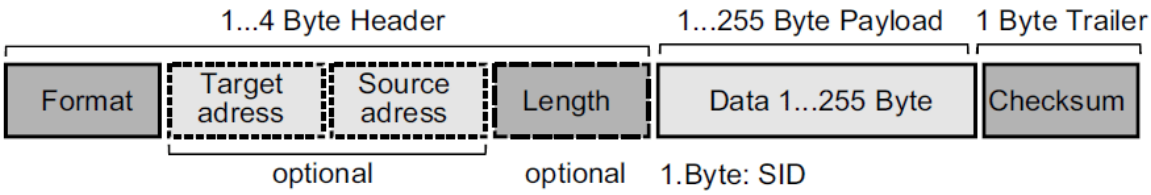


Figure 4.6: The KWP 2000 data format

The format byte indicates if the two optional address bytes (target and source address) are following or not. The optional length byte indicates how many data bytes are transmitted. The checksum is calculated using the modulo 256 addition over all bytes (excluding the byte for the checksum).

The addresses of the control units are set by the manufacturer and must be unique in the data network and as best in the whole vehicle bus system, which is called physical addressing. The standard recommends the address ranges:

- Engine Control: 10h – 17h;
- Transmission control:18h – 1Fh;
- ABS, ESC and TCS: 28h – 2Fh;
- Diagnostic devices: F0h – Fdh;

The diagnostic device has to know the addresses of the control units to start a communication. This is a disadvantage of the physical addressing for manufacturer independent test tools. OBD relevant components have to support the functional addresses 00h - 0Fh that manufacturer independent test tools, used by agencies like the MOT, can communicate with the control units and check emission relevant parameters. Functional addressing means in this context that the receiver address is specified.

The CAN bus uses identifiers for the addressing, which is explained in chapter 3.2. The emission relevant control units have the IDs 7DFh, 7E0h – 7EFh. Cars with gateways in the bus system use a remote address RA which indicates the sub network. The target address is the local address of the control unit.

Figure 4.7 shows the addressing of the control units, (Zimmermann/Schmidgall, 2007).

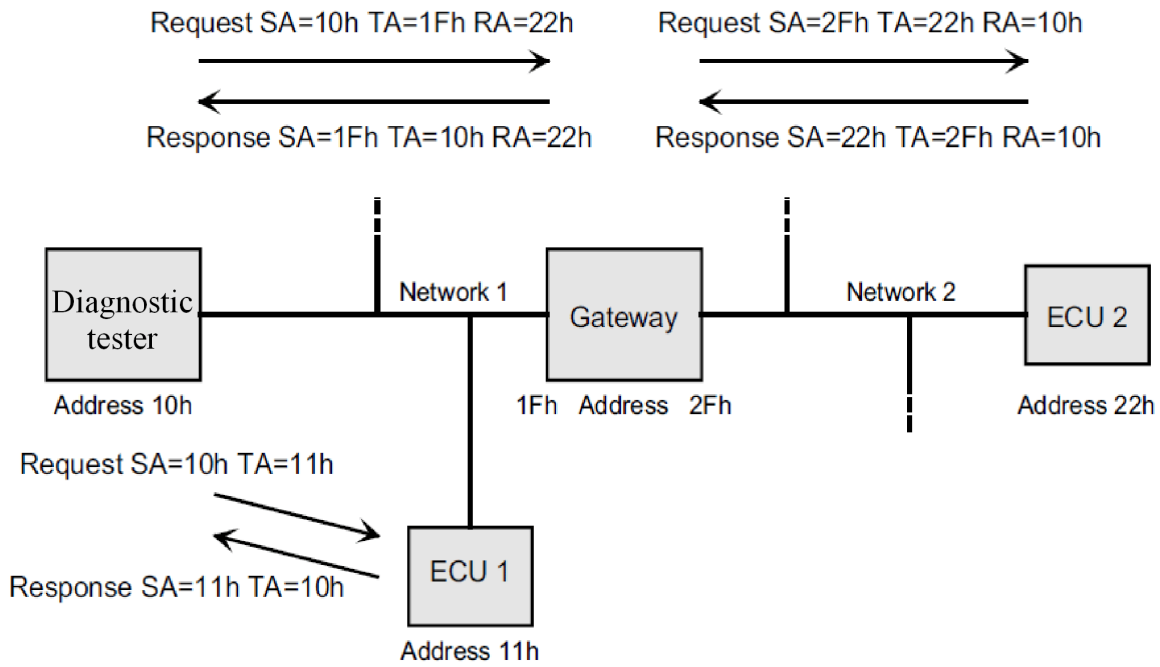


Figure 4.7: The KWP 2000 addressing

The communication services: The first byte of the data messages is the service identifier SID, which indicates the content of the message. Every request of the tester and the corresponding response of the control unit is fitted with an SID. Different SIDs are used for a positive or negative (error) response.

The SID for a positive response is the request SID with the sixth bit high. That is the request SID ORed with 40h.

Error handling: The tester and the control unit check the received messages for correctness. That means the correctness of data length, checksum and time out errors are checked. Control units ignore error messages and do not give a response. Therefore the test device recognises a time out error. The test device repeats a request up to three times when a response is faulty or missing.

Negative responses have the SID 7Fh followed by the received SID and an error code.

Example response error codes are:

SID	Meaning
10h	General reject
11h	Service not supported
12h	Sub function not supported
21h	Busy, repeat request
78h	Response pending
33h	Security access denied
35h	Invalid key
...	...

Table 4.2: Example of error codes

The start communication service request has the SID 81h. Stop communication service request has the SID 82h. Send data service using a SID supplied by the application layer. The following table shows defined SID by the standard.

	Request	Positive Response	Negative Response	Standardised in
OBD services	00 - 0Fh	40 - 4Fh	7F 00 - 7F 0Fh	SAE J1979/ISO 15031-5
Overall services for K-Line and CAN	10 - 3Eh	50 - 7Eh	7F 10 - 7F 3Eh	ISO 14230-3 and 15765-3
Escape Code	80h	C0h	7F 80h	ISO 14230-3 and 15765-3
K-Line services	81 - 83h	C1 - C3h	7F 81 - 7F 82h	ISO 14230-2
CAN services	94 - 85h	C4 - C5h	7F 84 - 7F 85h	ISO 15765-3
Manufacturer specific	A0 - BEh	E0 - FEh	7F A0 - 7F BEh	Manufacturer

Table 4.3: Standardised SIDs

The KWP 2000 can be structured in functional groups:

- Diagnostic Management;
- Network Layer Protocol Control;
- Data Transmission: Read and write control unit data;
- Stored Data Transmission: Read and write control unit fault memory;
- Input/Output Control: Triggering the I/Os of the control unit;
- Remote Activation of Routines;
- Up- and Download: Also called flashing the control unit;

Restrictions for emission relevant components

Exhaust relevant components like the engine control unit have special requirements:

- The target and source address byte must be used. Therefore the length byte is omitted in the message header. That means the header is at any time 3 byte.
- The payload of the messages has maximal 7 bytes.
- The communication is carried out with 10.4 kbit/s.

Diagnostic Management

A diagnostic session describes an operating mode of the control unit. The different diagnostic sessions are indicated with numbers:

Number	Type	Comment
81h	Default Diagnostic Session	Initial mode
85h	Programming Session	To flash the control unit
86h	Development Session	Special mode for system and control unit developer
87h	Adjustment Session	To adjust control unit parameters
89 - FEh	Manufacturer Specific Session	

Table 4.4: Diagnostic sessions

In initial mode the control unit is in a default diagnostic session and only limited diagnostic services are available due to security reasons. Assuming the control unit is in a default diagnostic session, the test device can request a special diagnostic session by sending a specific message shown in the table below:

Service	SID	Parameters and comments
Start Diagnostic Session	10h	1 byte session number
Stop Diagnostic Session	20h	Valid for K-Line; CAN switches to default session 81h
Security Access	27h	01h: Request Seed 02h: Send Key and manufacturer specific
Tester Present	3Eh	Keep alive message to hold a diagnostic session
ECU Reset	11h	The ECU acts like after switching on the power supply
Read ECU identification	1Ah	The requests of the control unit depends on the manufacturer

Table 4.5: Request of specific diagnostic sessions

The car manufacturer defines the conditions to start a diagnostic session and the supported services. General requirements are:

- To flash a control unit the car has to stand still and the engine must be turned off.
- An actuator test and access to the fault memory of the control unit can be executed when the car stands still and the engine is turned on and the car stands still.

The diagnostic tool has to identify itself using the seed and key method to unlock the ECU and getting access to certain diagnostic services. The seed and key method works as follows. The control unit sends an initialisation data (called seed), which is a random number to the test device. The test device calculates based on the received number a key and sends a security access – send key to the control unit. When the key values are equal the control unit changes the diagnostic mode and sends a positive response. The key and seed values as well as the calculation algorithm are not specified in the KWP standard. They are defined by the manufacturers. General diagnostic sessions are carried out with different keys for car manufacturers, control unit suppliers and authorised garages with different access levels. The differentiation is carried out with manufacturer specific security access messages whereby manipulations on the control units are prevented.

A time out mechanism is activated as long as the control unit is in a special diagnostic session to hold the connection between tester and control unit. The control unit stops a diagnostic session when it does not receive a message from the tester every five seconds. Then the control unit goes back to default mode. Therefore the test device sends every four seconds a tester presents message when no actual diagnostic message is sent to hold the connection.

A diagnostic session is closed with a stop diagnostic session message or the test device starts another diagnostic session by sending a start diagnostic session message. In this case the control unit goes back to the default diagnostic session, because the test device can have only one active diagnostic session. Using CAN as the physical layer the stop diagnostic session message should not be used and the session is closed with a start diagnostic session message (81h).

The read ECU identification message provides information about the manufacturer name, type, hard- and software version, serial number, data of production and more.

Fault memory

A central part for the current diagnostic concept is the fault memory. The following commands are used to read and erase the fault memory:

Service	SID	Comments
Read Diagnostic Trouble Codes	13h	Read single or all trouble codes with or without status information.
Read Diagnostic Trouble Codes By Status	18h	
Read Status Of Diagnostic Trouble Codes	17h	
Read Freeze Frame Date	12h	Read the environment data of the trouble codes
Clear Diagnostic Information	14h	Erase the fault memory

Table 4.6: Fault memory access

The number of the monitored defects and the storage capacity for faults depends on the control units and are very different. The fault memory has three categories which are the error code, status information and environment conditions. Several error codes are specified by government regulations which regards the exhaust gas treatment, specified in the ISO 15031-6. The exhaust trouble codes are read in the control units of the powertrain network.

Beside the standardised trouble codes, manufacturer depending codes exist, which can be accessed primly by manufacturer specific diagnostic scan tools. The trouble codes are mostly structured in powertrain (P), chassis (C), body (B) and network communication (U). The error code is 2 bytes long and the first two bits are used for structuring the error area. That means for every group there are over 16 000 (2^{16-2}) trouble codes available and every trouble code can display a single fault. Overall circa 65 000 errors can be identified in cars. But currently most of the error codes are in use and newer diagnostic protocols apply 3 byte long error codes. The following table shows the coding of the trouble codes.

Trouble Code Area	Group
00	Powertrain (P)
01	Chassis (C)
10	Body (B)
11	Network Communication (U)

Table 4.7: Coding of the trouble codes

The status information describes the current condition of the error. For example the error can appear sporadically or is present every time. The diagnostic system deals for different error states with different procedures. For example a break in the wire is a permanent fault which results in a replacement of the wire. A loose connection occurs the same trouble code but with different status information. This sporadic fault can be fixed through a check of the connector. Additional to the status information are environment values, like measurement and sensor data stored to indicate more accurately the fault conditions. This data supports the test tool to localise the cause of an error. Examples are sensor data of the engine speed measured in revolutions per minute (rpm) and the oil temperature. The sensor data indicates if the fault occurs on high or low rpm with a low operating temperature. The handling of the environment values depends on the manufacturer. That means some manufacturers have the same environment data for every trouble code and other manufacturer have different environment data for each trouble code.

The diagnostic check can also delete an error. This is possible when the fault is not detected in several diagnostic routines any more. Figure 4.8 shows an example of a fault entry, (Wallentowitz/Reif, 2006).

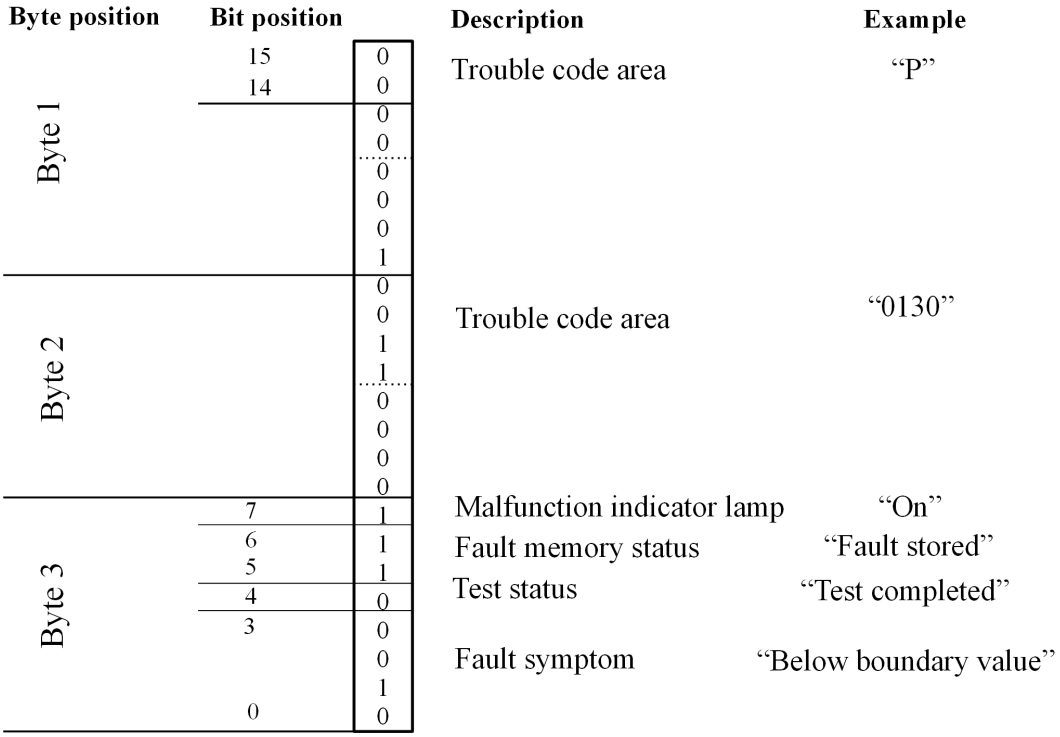


Figure 4.8: Example of a fault entry in the control unit

4.2.2. Unified Diagnostic Services UDS

The UDS standard is the merging of the ISO 14230-3 (KWP 2000), the 15765-3 (Diagnostic over CAN) and the General Motors specification GMLAN with the aim to reduce the cost of diagnostic communication systems. UDS is available for the CAN bus. Further bus systems like FlexRay or LAN will use the standard in the future as well. The UDS is compared to the previous standard more effective and more services can be used but also the standard is more complex. 25 Diagnostic Services are defined and in the table of appendix A. The table is structured in functional classes and the availability in a diagnostic default session is indicated. The amount of SIDs is tightened by merging KWP 2000 services in a subfunction of the UDS. Picking a subfunction is performed by requesting the new parameter subfunction level (LEV). Allowed values for LEV are between 00h – 7Fh. The seventh bit of LEV is to control the communication.

Also UDS provides the option to perform an encrypted data transmission. The encryption is carried out after the principle described in the ISO 15764. The encryption and decryption take place on an extra protocol layer, called security layer, which is implemented between the control unit and the test tool application and the UDS application layer, shown in figure 4.9, (Zimmermann/Schmidgall, 2007).

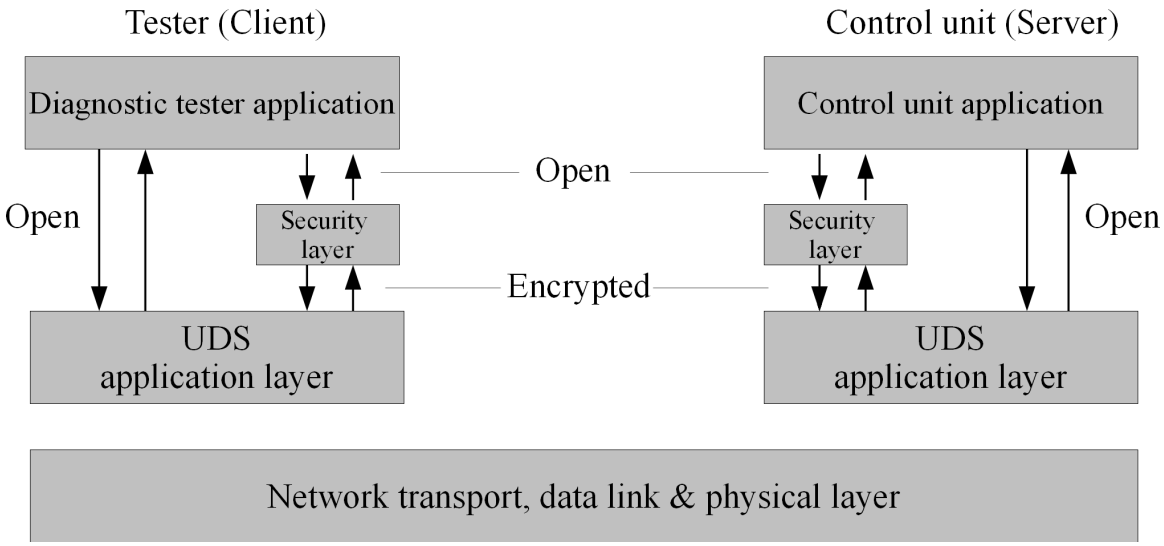


Figure 4.9: The UDS application layer

A further implementation in UDS is the response on event service. This service allows the test tool to install an event trigger on the control unit. On triggering an event in the control unit, it automatically sends a request message to the tester. The process is as follows:

- Installing the event trigger with a trigger condition and a trigger time frame with the access timing parameter.
- Starting the event service using start response on event.
- Sending requests when an event occurred by the control unit to the tester.
- The event service is stopped after expiration of the trigger time frame or by the test tool.
- Uninstalling the event service.

Following events can be triggered in the control units:

- On diagnostic trouble code status change.
- On change of data identifier.
- On comparison of values.

Following services can be applied on the event by the control unit:

- Read data by identifier SID = 22h.
- Read diagnostic trouble code information SID = 19h.
- Routine control SID = 31h.
- Input/Output control by identifier SID = 2Fh.

With Read scaling data is now a service available to read the scaling and standard of the internal controller data. That means to figure out the correlation between the stored value in hex format and the actual physical value. Therefore the used unit (miles, km/h, temperature etc.), the scaling factor (offset and rising of the conversion formula) and number representation (integer, binary coded decimal/or floating point, numbers of bits) is identified. The conversion formula is:

$$Physical\ value = Hex\ value \times rising + offset$$, (Wallentowitz/Reif, 2006).

4.2.3. The On Board diagnostic OBD

The on board diagnostic is distributed over several control units in the car which are dealing with exhaust relevant components. Examples are the catalyst or the oxygen sensor.

The OBD-2 connector is installed in any vehicle permitted in Europe since 2001 for cars with gasoline engines and since 2003 with diesel engines. The on board diagnostic has been developed for monitoring emission related systems and parameters of vehicles. The OBD connector provides the pins for the K-line, the CAN bus and J1850 and is standardised in the ISO 15031-3 and SAE J1962. The connector is fitted in the surrounding of the steering wheel. Typical locations are next to the fuse box inside the car or underneath the ashtray. Figure 4.10 shows the OBD connector and the following table explains the pin functions, (Zimmermann/Schmidgall, 2007).

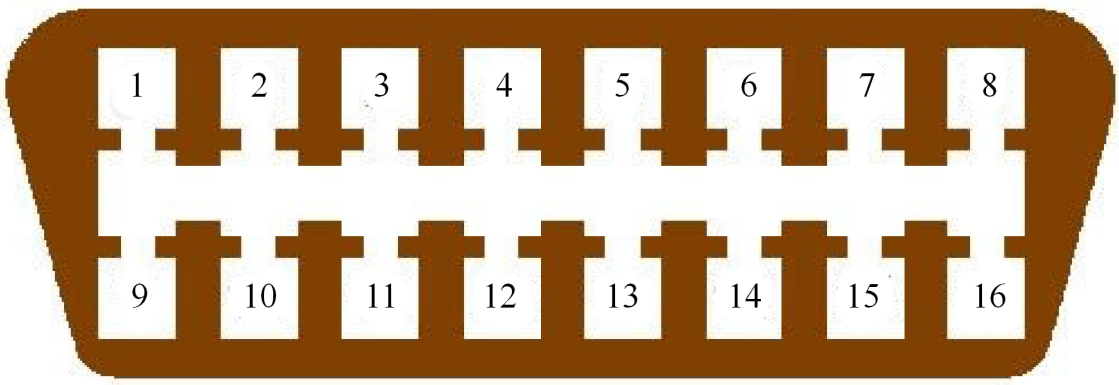


Figure 4.10: The OBD connector

Pin	Description
1	blank
2	J1850 + Bus
3	blank
4	Chassis Ground
5	Signal Ground
6	CAN High
7	ISO 9141-2 K Line
8	blank
9	blank
10	J1850 - Bus
11	blank
12	blank
13	blank
14	CAN Low
15	ISO 9141-2 L Line
16	Battery voltage

Table 4.8: Pins of OBD connector

The blank pins can be used by the car manufacturers for own functions.

The communication of the diagnostic data is summarized in the ISO 15031 which is almost identical to the American SAE standard. The following table gives an overview of the standardisation.

Topic	ISO Standard	SAE Standard
General Information	ISO 15031-1	-
Terminology and Abbreviations	ISO 15031-2	J1930
Connector	ISO 15031-3	J1962
OBD Scan Tool	ISO 15031-4	J1978
Diagnostic Service	ISO 15031-5	J1979
Diagnostic Trouble Codes	ISO 15031-6	J2012
Data Link Security	ISO 15031-7	J2186

Table 4.9: Standardisation of the diagnostic communication

The standard also allows the K Line and CAN bus using the KWP 2000 protocol. The predecessor of the K-Line, the ISO 9141-2 CARB and the SAE J1850 bus are using PWM. Typically in a car only one bus system for diagnostic applications is supported. The diagnostic testers are able to deal with every protocol and identify the used bus.

The OBD has following functions:

- Continuous monitoring of exhaust relevant systems (e.g. oxygen sensor).
- Permanent storage of diagnostic trouble code in the fault memory. Examples are errors in the ignition systems or the status of service intervals.
- Display errors for the driver using the MIL.
- Communication with an external scan tool.

The OBD request/response messages have the KWP 2000 format, described in chapter 4.2.1 and the test tool has to use the functional addressing. The OBD relevant control units have the functional address 33h and the tester F1h. As mentioned before, more than one control unit will react on the functional address and the test tool has to expect more then one response. The tester can differentiate the control units with response messages and the included explicit physical address.

The messages are maximal seven bytes long including six data bytes and a SID byte. The first data byte of a request message is to identify parameters (PID), e.g. data values of the control unit. The table in appendix B shows the OBD services.

Reading the fault memory

In the beginning of a diagnostic session the test tool checks vehicle identification and the software-/hardware version of the control unit with a *Service 09h Request Vehicle Information*. After this MIL status and the number of control units in the car is read using the SID = 01h and PID = 01h *Request Current Power Train Diagnostic Data*.

The first byte of the control unit response is the MIL status (bit seven = 1 means the MIL is turned on) and the remaining seven bits of the first byte show the number of stored faults.

The second byte shows which monitoring functions are implemented in the car:

- Bit 0 = 1: Monitoring system for the ignition;
- Bit 1 = 1: Monitoring system for the injection;
- Bit 2 = 1: Other monitoring systems;
- Bit 4 to 6 shows if the monitoring systems performed a complete test cycle which means if the monitored data are valid;

The third byte shows which components are monitored:

- Bit 0: Catalyst;
- Bit 1: Catalyst heating;
- Bit 2: Fuel tank ventilation;
- Bit 3: Secondary air system;
- Bit 4: Air condition cooling medium;
- Bit 5: Oxygen sensor;
- Bit 6: Lampda probe heating;
- Bit 7: Exhaust gas recirculation;

The fourth byte shows bit by bit which component was monitored in a complete test cycle.

In the next step the tester reads the OBD relevant trouble code using the *Service 03h Request Emission Related Diagnostic Trouble Codes* command. The request of the control unit contains three 16 bit trouble codes. In the case of no stored trouble codes, the trouble code is set to 0000h. When more then three faults are stored the control unit sends more response messages. The tester knows how many responses are sent by the control unit due to the previous request SID = 01h and PID = 01h.

The tester can request stored environment data to every trouble code. All environment data are stored in hex format (n = 8 or n = 16 bit) which can be recalculated in the actual physical value using the formula:

$$Physical\ value = \frac{Decimalvalue}{(2^n - 1)}(Maximal\ value - Minimal\ value) + Minimal\ value$$

and the range of values is shown in the appendix C.

The calculation for cooling water is shown in an example:

Stored hexadecimal value: 36h = 54 (decimal)

Calculating the physical value: $\frac{54}{(2^8 - 1)}(215\,°C - (-40\,°C)) + (-40\,°C) = 14\,°C$

4.3. The new diagnostic approach

As described in the chapter 4.2 the current approach allows only a small part of diagnostic services of the control units during normal driving due to security reasons, which is a disadvantage of the current diagnostic approach. In driving mode reading the fault memory of the control units is very limited or not possible. Therefore the driver does not receive detailed error information in case of a defect on the vehicle. It is not possible for the driver to estimate how serious an error and how secure driving on is, (Zimmermann/Schmidgall, 2006).

As explained in chapter 4.1. the current diagnostic approach uses single control units to detect their own faults and the errors of the integrated sensors. But over the past decades the numbers of control units has constantly increased and new functions are distributed over several control units of the car, (You/Krage/Jalics, 2005).

In summary the current used diagnostic approach has the following problems and disadvantages:

- A single fault can affect several different control units caused by the network explained in chapter 1.3.
- Over the past years several different standards have been used described in chapter 4.1.
- Limited diagnostic services are available while the car is in driving mode explained in chapter 4.2.

- Until now the cross linking and the communication between the different control units has not considered to detect vehicle faults.

These are the points where the new diagnostic approach has advantages, using the bus level as fault detection method. After our theory the bus level changes between faultless and faulty vehicle condition. The transmitted messages of the sensors and control units are different depending on the condition of the car.

The onboard diagnostic method has to be improved with a function of analysing the bus level, which has the following advantages against the current offboard diagnostic method:

- An optimized onboard diagnostic method provides more detailed fault information and hence supports the development of improved vehicles;
- Through the accurate presentation of error information no parts of the car are replaced on suspicion. This decreases repairing costs and time.
- The detailed error information is available at any time for the driver as soon as the ignition is switched on. The error is indicated as soon as the fault occurs and safe driving is possible at any time.
- The possession and acquisition of expensive offboard diagnostic tools for garages and the MOT is no longer necessary. A fault memory embedded in the control units is needless.

As fault detection method a theory is developed which uses the bus level as fault indicator. The new onboard diagnostic tool is able to communicate with each connected bus user. This means:

- The sensor data can be checked for plausibility by analysing the transmitted messages over the vehicle bus network.
- Ability to query controller and actuator condition by sending status messages over the vehicle bus network.
- The detection of incorrect commands of the control units for actuators or other control units by analysing the messages on the vehicle CAN bus network.

In case of fault detection the tool is able to present the error information on a display.

Chapter 5

The Development & Design of a Diagnostic Node

In this chapter the development of an interface to the in-vehicle bus system is described, which is needed to use the bus level theory as a fault indication method. Also an expansion with a USB host interface and a connection to a LCD display is shown which can be used for a new diagnostic tool. The chapter starts with the explanation of used tools, the required components as well as the hardware design and finally the experimental tests are shown.

5.1. Hardware development tools

5.1.1. The Atmel STK 600

The STK 600 is a complete starter kit and a development system for AVR flash microcontrollers. It is designed to give a quick start to develop code on the AVR and to test new designs and prototypes. The main features of the STK600 are:

- AVR Studio 4 compatible;
- USB interface to a PC for programming and control;
- Serial In-System and JTAG Programming of AVR devices;
- Flexible routing and socket card system for easy mounting of all supported devices;
- 8 LEDs for general use;
- 8 push buttons for general use;
- All AVR I/O ports are easily accessible through pin header connectors;

The STK 600 is shown in figure 5.1, (Atmel, 2009).

Figure 5.1: Atmel STK600

5.1.2. The Atmel JTAGICE mkII

The Atmel JTAGICE mkII, shown in figure 5.2 supports on chip debugging and programming of all AVR 8 and 32 bit microcontrollers with on chip debug capability. The main features are:

- Fully compatible with AVR Studio 4;
- Supports debugging (software breakpoints, program memory breakpoints) of all AVR microcontrollers with on chip debug capability;
- Programming interface to flash, eeprom, fuses and lockbits;

Figure 5.2: Atmel JTAGICE mkII

5.1.3. AVR Studio 4

AVR Studio is an integrated development environment (IDE) for writing and debugging AVR applications in Windows environments. AVR Studio provides a project management tool, source file editor, simulator, assembler and front-end for C/C++ programming, emulation and on-chip debugging.

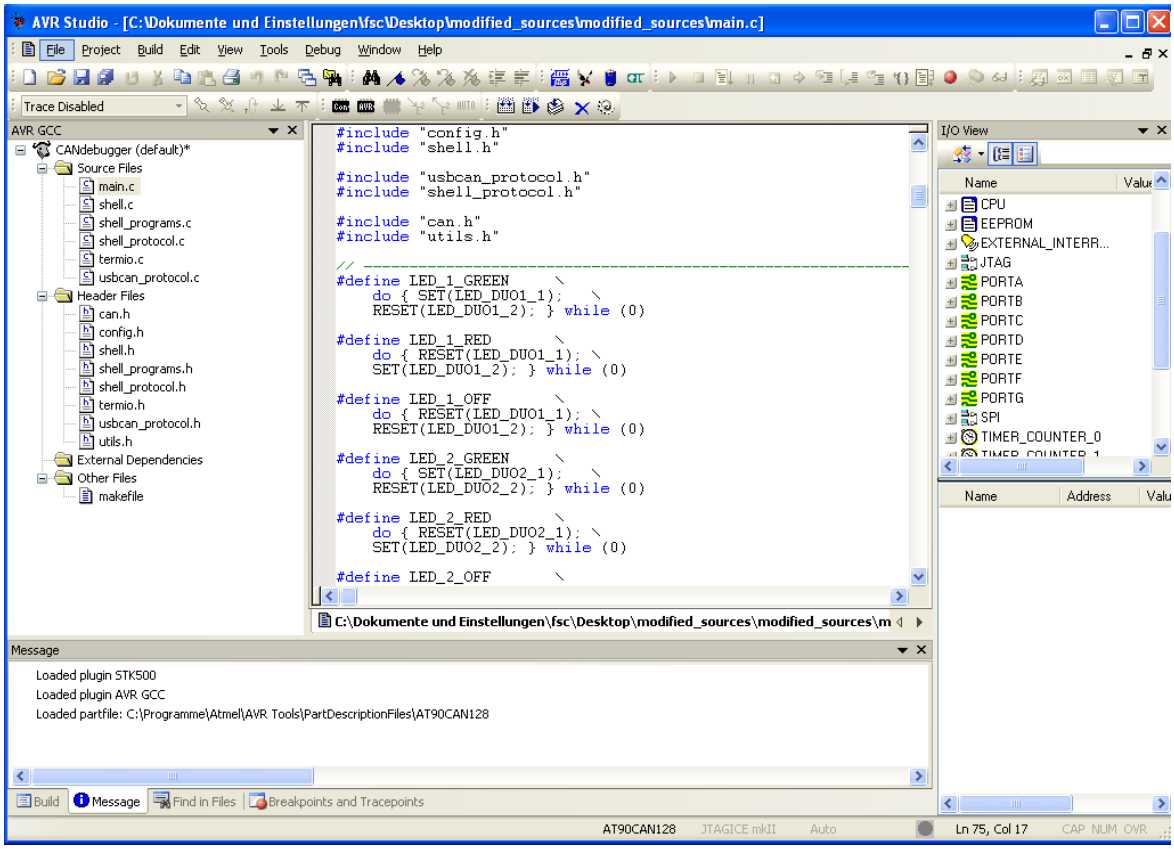


Figure 5.3: AVR Studio screenshot

5.1.4. Eagle

Eagle is the short form of **E**asy **A**pplication **G**raphical **L**ayout **E**ditor and is an easy to use tool for designing printed circuit boards. The eagle light edition is free for non profit applications and has the following limitations:

- The usable board area is limited to 100 x 80 mm;
- Limited to two signal layers (top and bottom);
- Only one sheet can be created in the schematic editor;

The program consists of three main modules which are embedded in a single user interface:

- Layout Editor;
- Schematic Module;
- Autorouter;

The layout editor

The layout editor allows us to design printed circuit boards and includes the library editor, the CAM processor and the text editor. In the library editor are design packages (footprints), symbols and devices for creating a schematics. The CAM Processor provides a job mechanism with the aid of which the creation of the output data for a board can be automated.

The schematic module

The circuit board can be generated at any time by a mouse click and the circuit diagram can be drawn. Eagle then changes to the Layout Editor, where the packages are placed next to an empty board - connected via airwires (rubber bands). Schematic and layout are automatically kept consistent by EAGLE using forward and back annotation.

Autorouter

The airwires can be routed automatically with the autorouter module. It can be chosen between single nets, groups of nets or all nets for the automatic routing pass using the auto command. The program will handle various network classes having different track widths and minimum clearances, (Eagle, 2010).

5.2. Hardware components

5.2.1. The microcontroller AT90CAN128

The used microcontroller in this project is an 8-bit Atmel AT90CAN128. The AT90CAN128 uses the AVR RISC architecture and allows an output of 1 MIPS per MHz in a single clock cycle.

The AVR has 32 general working registers which are directly connected to the Arithmetic Logic Unit ALU. Therefore the ALU has access to two independent registers and one single instruction can be executed in one clock cycle which is up to ten times faster than conventional CISC microcontrollers.

Further features of the AT90CAN128 are:

- 128 kBytes in system programmable flash with read/write capabilities;
- 4 kByte EEPROM;
- 4 kByte SRAM;
- 53 general purposes I/O lines;
- 32 general purposes working registers;
- CAN controller;
- Real Time Counter RTC;
- Four flexible Timer/Counters with compare modes and PWM;
- Two USARTs;
- Two wire serial interface (byte orientated);
- 8 channel 10 bit ADC with differential input stage and programmable gain;
- Programmable Watchdog Timer with internal oscillator;
- A serial peripheral interface SPI;
- Joint test action group JTAG interface after IEEE standard 1149.1;

Figure 5.4 shows the pin configuration of the AT90CAN128 and in appendix D are the pin functions described, (Atmel, 2008).

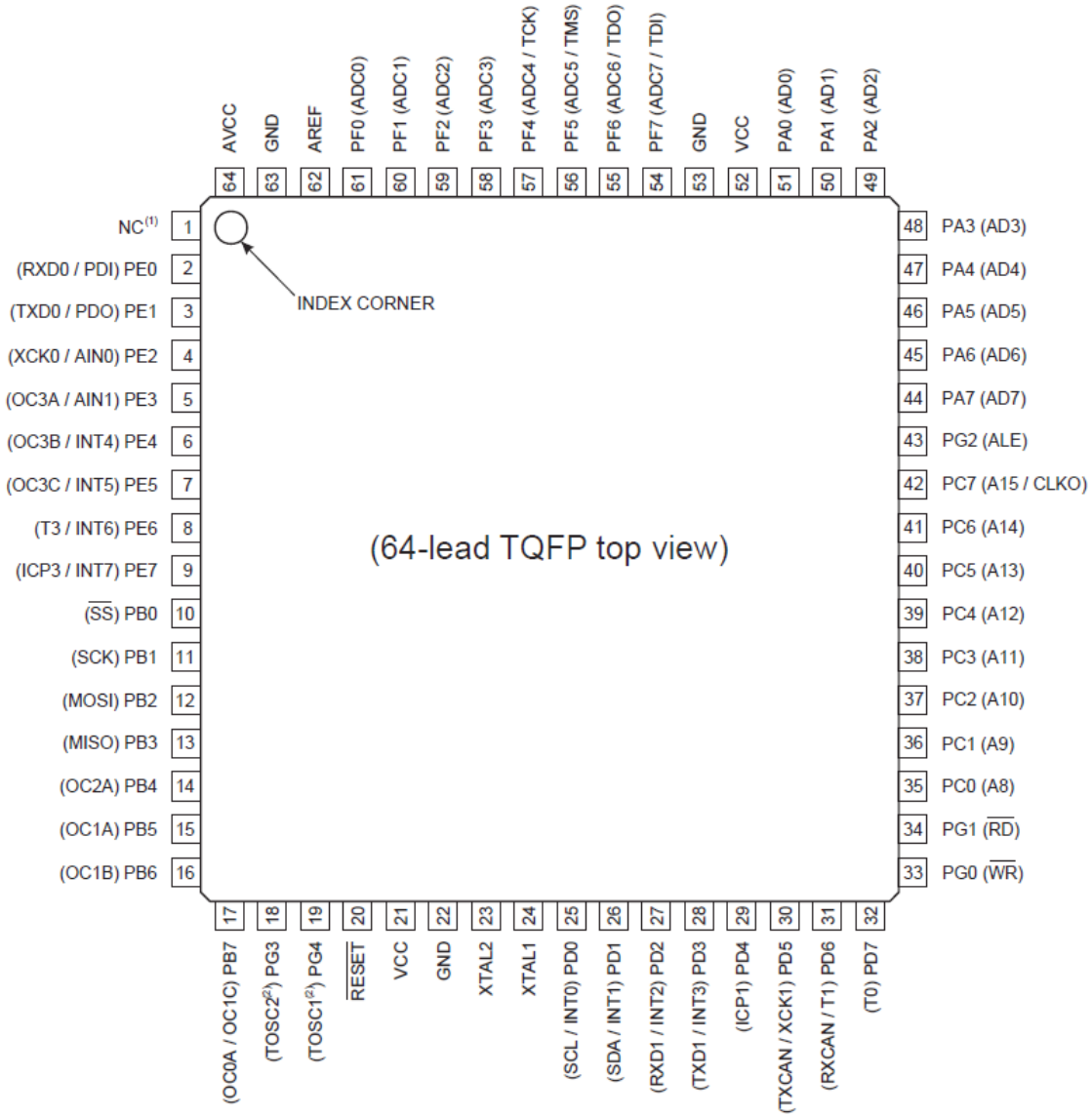


Figure 5.4: The AT90CAN128 pin layout

5.2.2. The CAN Transceiver PCA82C251

The PCA82C251 is the interface between the CAN protocol controller and the physical bus. It is primarily intended for applications up to 1 Mbaud in cars, trucks and buses. The device provides differential transmit capability to the bus and differential receive capability to the CAN controller. It is fully compatible with the “ISO 11898-24 V” standard. Figure 5.5 shows the pin configuration.

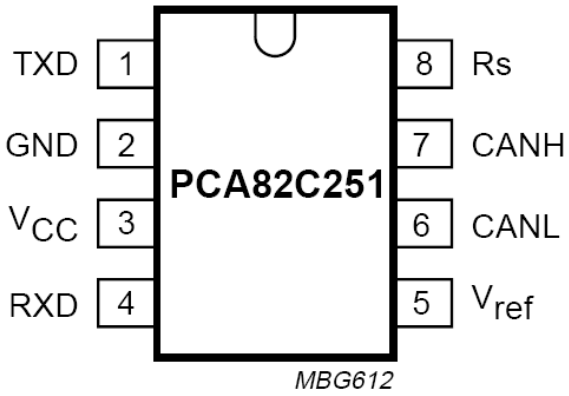


Figure 5.5: The CAN transceiver pin layout

Pin #	Signal	Description
1	TXD	Transmit data input.
2	GND	Ground.
3	V_{CC}	Supply voltage.
4	RXD	Receive data output.
5	V_{ref}	Reference voltage output.
6	CANL	CAN low level voltage input/output.
7	CANH	CAN high level voltage input/output.
8	Rs	Slope resistor input.

Table 5.1: CAN transceiver PCA82C251 pin description

A current limiting circuit protects the transmitter output stage against short-circuit to positive and negative battery voltage. Although the power dissipation is increased during this fault condition, this feature will prevent destruction of the transmitter output stage.

If the junction temperature exceeds a value of approximately 160 °C, the limiting current of both transmitter outputs is decreased. Because the transmitter is responsible for the major part of the power dissipation, this will result in reduced power dissipation and hence a lower chip temperature. All other parts of the IC will remain operating. The thermal

protection is particularly needed when a bus line is short-circuited.

The CANH and CANL lines are also protected against electrical transients which may occur in an automotive environment.

Pin 8 (Rs) allows three different modes of operation to be selected: high-speed, slope control or standby.

- For high-speed operation, the transmitter output transistors are simply switched on and off as fast as possible. In this mode, no measures are taken to limit the rise and fall slope. Use of a shielded cable is recommended to avoid RFI problems. The high-speed mode is selected by connecting pin 8 to ground.
- The slope control mode allows the use of an unshielded twisted pair or a parallel pair of wires as bus lines. To reduce RFI, the rise and fall slope should be limited. The rise and fall slope can be programmed with a resistor connected from pin 8 to ground. The slope is proportional to the current output at pin 8.
- If a HIGH level is applied to pin 8, the circuit enters a low current standby mode. In this mode, the transmitter is switched off and the receiver is switched to a low current. If dominant bits are detected (differential bus voltage >0.9 V), RXD will be switched to a LOW level. The microcontroller should react to this condition by switching the transceiver back to normal operation (via pin 8). Because the receiver is slower in standby mode, the first message will be lost at higher bit rates.

  (Philips, 2000)

For the hardware layout the default mode is applied.

5.2.3. The USB FIFO FT245BM

The FT245BM provides a method of transferring data to/from a peripheral and a host PC at up to one megabyte per second. The FIFO like design gives an interface to any microcontroller or microprocessor via I/O ports.

By using FTDI's virtual COM port drivers, the peripheral looks like a standard COM port to the application software. Commands to set the baud rate are ignored - the device always

transfers data at its fastest rate regardless of the applications baud-rate setting.

Figure 5.6 shows the pin configuration and in appendix E the pin functions are described, (FTDI, 2005).

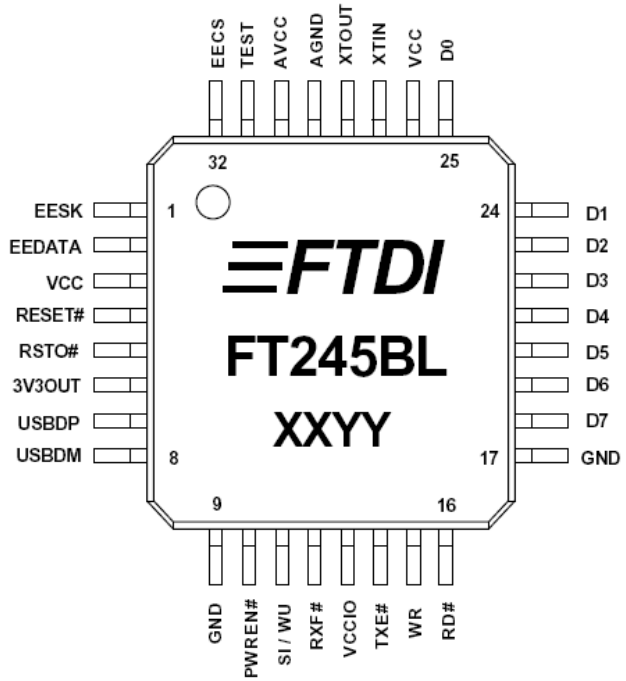


Figure 5.6: The FT245 pin layout

5.2.4. The VNC1L and VDIP1

The VNC1L is an embedded USB host controller integrated circuit device. The controller is used to store data on a USB flash drive when the prototype of the new diagnostic tool detects a fault. This provides an easier method to analyse error data for garages and the MOT.

The Vinculum can also encapsulate certain USB device classes handling the USB host interface and data transfer functions using the in-built microcontroller and embedded flash memory. When interfacing to mass storage devices, such as USB flash drives, Vinculum transparently handles the FAT file structure using a simple to implement command set. Vinculum provides a solution for introducing USB host capability.

The VNC1L has a Combined Interface which interfaces a controlling application with the

Command Monitor. The combined interfaces are UART, Parallel FIFO and SPI.

The key features of the VNC1L are:

- Two independent USB host ports;
- 8 or 32-bit microcontroller core;
- 64k embedded flash program memory;
- 4k internal data SRAM;
- 2 x USB 2.0 slow speed or full speed host or slave ports;
- Automatic low or full speed selection;
- UART, SPI and Parallel FIFO interfaces;
- Up to 28 general purpose I/O pins depending on configuration;
- Low power operation (25mA running/2mA standby);

There are currently 6 standard firmware versions available for the VNC1L:

- VDAP Firmware: USB host for single flash disk and general purpose USB peripherals. Selectable UART, FIFO or SPI interface command monitor.
- VDPS Firmware: USB host for single flash disk and general purpose USB peripherals. USB slave port connection for connecting to host PC. Selectable UART, FIFO or SPI interface command monitor.
- VDFC Firmware: USB host for two flash disks, selectable UART, FIFO or SPI interface command monitor.
- VMSC1 Firmware: USB host for single flash disk and general purpose USB peripherals. Audio playback command extensions for MP3 decoder integrated circuits. Selectable UART, FIFO or SPI interface command monitor port.
- VCDC Firmware: USB Host for automatic connection to USB communications class devices. UART interface command monitor.
- VDIF Firmware: USB host for single flash disk and general purpose USB peripherals. Selectable UART, FIFO, SPI or USB interface command monitor.

General purpose USB peripherals including printers, communication class devices, human interface devices, FTDI USB serial devices, and USB hubs. USB peripherals can be accessed using command monitor commands to send SETUP, DATA IN and DATA OUT packets. Flash disk firmware supports FAT12, FAT16 and FAT32 file systems with a simple file oriented command set.

For the development of the VNC1L design the VDIP1 module is used. The VDIP1 is supplied on a PCB designed to fit into a 24 pin DIP socket, and provides access to the UART, parallel FIFO, and SPI interface pins on the VNC1L device, via its AD and AC bus pins.

The VDIP1 module has following features:

- Uses FTDI´s VNC1L embedded dual USB host controller integrated circuit device.
- USB single “A” type USB socket to interface with USB peripheral devices.
- Second USB interface port available via module pins if required.
- Jumper selectable UART, parallel FIFO or SPI microcontroller interface.
- Single 5V supply input from USB connection.
- Auxiliary 3.3V / 200mA power output to external logic.
- Program or update firmware via USB flash disk or via UART/parallel FIFO/SPI interface.
- VNC1L firmware programming control pins PROG# and RESET# brought out onto jumper interface.

Figure 5.7 shows the pin configuration of the VNC1L and of the VDIP1 module. In appendix F the pin functions are described, (FTDI, 2009).

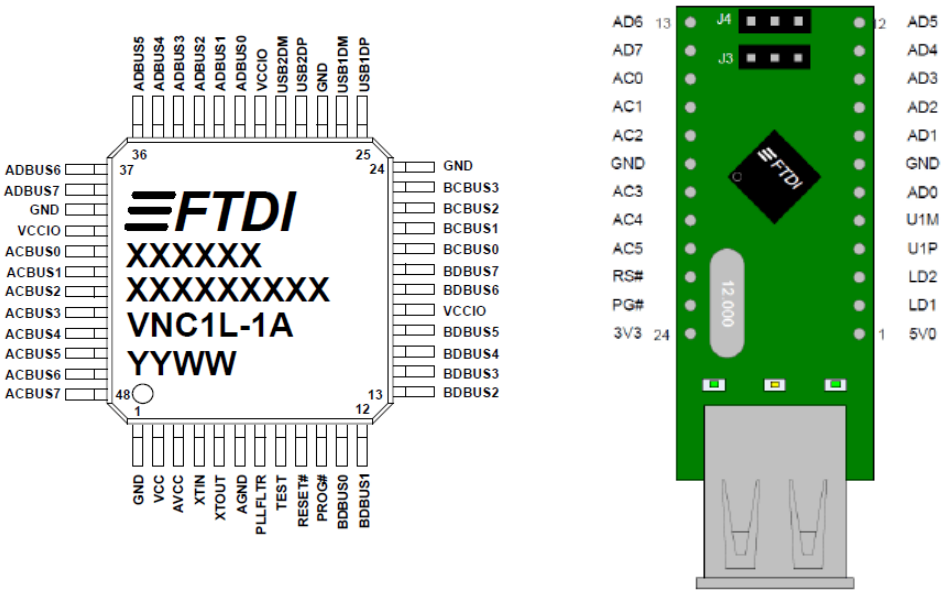


Figure 5.7: The VNC1L and VDIP1 pin layout

5.2.5. LC Display WD-C2704M-1HNN

The LCD WD-C2704M-1HNN is used to indicate the faults as soon as they occur and provides an example interface of multimedia displays used in cars. The display has the shown features:

- Four lines x 27 digits text;
- Integrated controller HD44780;
- Two separate controller for the upper and bottom display half;
- Accessed over four or eight bit data bus;
- Supply voltage of 5V/6mA;

Pin layout:

Pin	Function
1	GND
2	V_{CC}
3	V_o (Contrast settings)
4	RS
5	R/W
6	E1 (Controller upper display half)
7	E2 (Controller bottom display half)
8	D0
9	D1
10	D2
11	D3
12	D4
13	D5
14	D6
15	D7
16 - 21	Connected to contact area for eight rubber buttons

Table 5.2: LCD WD-C2704M-1HNN pin description

5.3. Hardware design of the CAN circuit

The primary layout and software was developed by the RWTH Aachen robotic club and is used as basis. The project is licensed under general public license (GPL) and can be used for all purposes without limitations, as well as commercially, (Greif, 2008).

5.3.1. Connecting the AT90CAN128

Crystal oscillator

XTAL1 and XTAL2 are input and output, respectively, of an inverting amplifier which can be configured for use as an on-chip oscillator, as shown in figure 5.7. Either a quartz crystal or a ceramic resonator may be used. In the layout a 16MHz crystal is used.

C1 and C2 should always be equal for both crystals and resonators. The optimal value of

the capacitors depends on the crystal or resonator in use, the amount of stray capacitance, and the electromagnetic noise of the environment. Some initial guidelines for choosing capacitors for use with crystals are given in the datasheet of the AT90CAN128. The optimal capacitor value for a 16Mhz crystal is 22pF which is good for many crystals. The FT245BM uses as 6MHz crystal and the VNC1L a 12MHz crystal. How to connect a crystal is shown in figure 5.8, (Atmel, 2008).

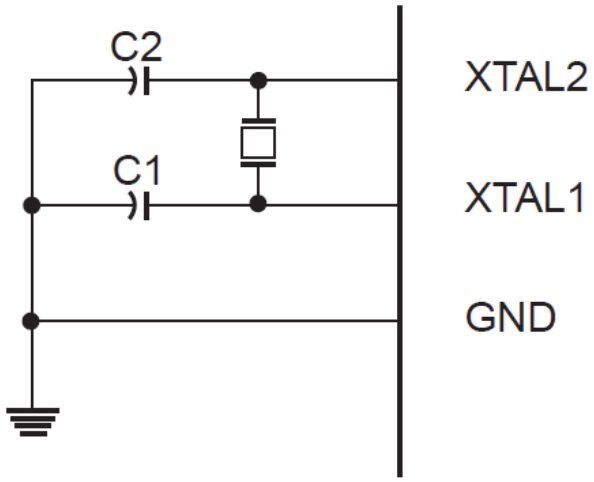


Figure 5.8: The wiring of the crystal

Reset

The reset pin of the AT90CAN128 is "active low", which means connecting the pin to ground is a reset. The microcontroller has a high resistive internal pullup resistor which pulls the reset pin against V_{CC}. In some cases the resistance of the pullup resistor is not enough and it is recommended to connect an external pull up resistor between reset pin and V_{CC}. The typical value is 10 kΩ. Additionally it is recommended to connect a capacitor between the reset pin and ground. The capacitor ensures that the controller is reset for a defined period while turning on the supply voltage. While the microcontroller is running the capacitor ensures that the reset input is not sensitive to spikes and glitches. Therefore the capacitor should be connected very close to the microcontroller, (Atmel, 2010).

Miscellaneous

- The voltage reference for the ADC is externally decoupled at the AREF pin by a capacitor with 100nF for better noise performance.
- The CAN data from the AT90CAN128 are parallel transmitted directly from port A to the data bus of the FT245BM. Also port G is used for the strobe control.
- Five LEDs are connected using port PF3-PF7, PG3/4 and PD7 of the AT90CAN128 to indicate the modus shell or COM, sending/receiving CAN messages and the power status.

  The series resistor for the LEDs is calculated using the $R = \frac{(V_{CC} - V_{LED})}{I_{LED}}$ formula. In the present case is V_{CC} 5 V, V_{LED} is 1.9V for the green LED and 2.1V for the duo LEDs using data sheet information. I_{LED} is 5mA for the green LED after figure 5.9 given in the datasheet as well, (Kingbright Elec., n.d).

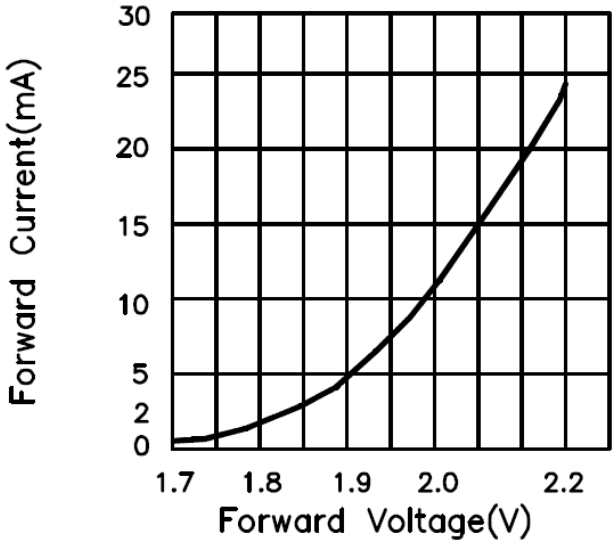


Figure 5.9: Characteristic of the LED forward current vs. forward voltage

Therefore the calculated series resistor is 620Ω for the green LED. The next standardised resistance value is 680Ω, which is used in the circuit layout.

- Jumper 1 is a button to short circuit the pins PB4 and PB5 which changes the

modus of the device.

- The MOSI/MISO wires of the ISP programmer are connected to PE0/PE1, which are the inputs for serial programming of the AT90CAN128.
- PD5 and PD6 are connected to the CAN transceiver over the dual channel digital oscillator ADUM1201 which enables a galvanic isolation between measuring circuit and the measured CAN bus. For the power supply for the components in the galvanic area (the ADUM1201 and the CAN transceiver) a DC/DC converter is used.
- On PC0 a relay is connected over a series resistor with the value of 2.2kΩ and an NPN bipolar transistor to switch on/off a 120Ω resistor. The flyback diode needs to be connected to eliminate flyback of the sudden voltage spike across of an inductive load when its supply voltage is suddenly removed or reduced.

5.3.2. Connecting the FT245BM

EEPROM

Figure 5.10 illustrates how to connect the FT245BM to the 93C46, 93C56 or 93C66 EEPROM. EECS (pin 32) is directly connected to the chip select (CS) pin of the EEPROM. EESK (pin 1) is directly connected to the clock (SK) pin of the EEPROM. EEDATA (pin 2) is directly connected to the Data In (Din) pin of the EEPROM. There is a potential condition whereby both the data output (Dout) of the EEPROM can drive out at the same time as the EEDATA pin of the FT245BM. To prevent potential data clash in this situation, the Dout of the EEPROM is connected to EEDATA of the FT245BM via a 2.2 kΩ resistor.

Following a power-on reset or a USB reset, the FT245BM will scan the EEPROM to find out:

a) If an EEPROM is attached to the device.

b) If the data in the device is valid.

If both of these is the case, the FT245BM will use the data in the EEPROM, otherwise it

will use its built-in default values. When a valid command is issued to the EEPROM from the FT245BM, the EEPROM will acknowledge the command by pulling its Dout pin low. In order to check for this condition, it is necessary to pull Dout high using a 10 kΩ resistor. If the command acknowledge does not happen then EEDATA will be pulled high by the 10 kΩ resistor during this part of the cycle and the device will detect an invalid command or no EEPROM present, (FTDI, 2005).

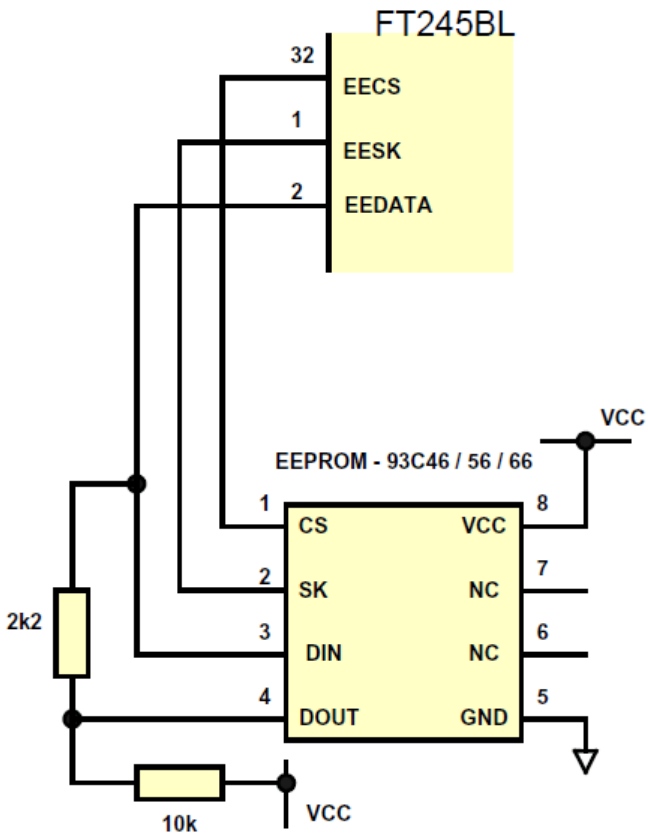


Figure 5.10: Wiring of the FT245 to an EEPROM

Bus powered circuit with power control

Figure 5.11 shows an example of a 5 volt, USB bus powered design using the FT245BM connected to a 5V microcontroller or other external logic. In this design, the FT245BM controls the power to the auxiliary circuitry using PWEREN# to shut off power to this

circuitry when: The FT245BM is in reset, or the FT245BM has not yet been configured (successfully recognised and enumerated over USB), or USB is in suspend/sleep mode.

- A P-channel logic level MOSFET is used as a power switch to control the power to the auxiliary devices – in the example of FTDI is the rectifier IRLML6402 used. In the final design the IRF7416 MOSFET is used.

  It is recommended that a "soft start" circuit consisting of a 1kΩ series resistor and a 0.1µF capacitor are used to limit the current surge when the MOSFET turns on. Without this, there is a danger that the transient power surge of the MOSFET turning on will reset the FT245BM or the USB host/hub controller. The values used allow the attached circuitry to power up with a slew rate of ~ 12.5V per millisecond, in other words the output voltage will transition from GND to 5V in around 400 microseconds.

- When this circuit is used, the "pull-down on suspend" option in the EEPROM must be enabled. This will ensure minimum leakage current during sleep (suspend) mode by gently pulling down the FIFO interface pins of the FT245BM pins to GND during USB suspend.

- The auxiliary circuitry attached to the FT245BM device must have its own power-on-reset circuitry and should not use RESETO# to generate a reset for this circuitry. RESETO# does not generate a reset during USB sleep (suspend) when the auxiliary logic is powered-off, thus cannot be used as a reset in this case.

- A "USB high-power bus powered device" (one that consumes more than 100mA and up to 500mA) of current from the USB bus during normal operation must use this power control feature to remain compliant as the USB specification does not allow a USB peripheral to draw more than 100mA of current from the USB Bus until the device has been successfully enumerated. A "USB high-power bus powered device" cannot be plugged into a USB Bus-Powered Hub as these can only supply 100mA per USB port.

- The power (current) consumption of the device is set in a field in the 93C46 EEPROM attached to the FT245BM. A "USB high-power bus powered device"

must use the 93C46 to inform the system of it's power requirements. Also the EEPROM can be used to customise the USB VID, PID, serial number, product description strings of the FT245BM. Other parameters are controlled by the EEPROM including remote wake up, isochronous transfer mode, soft pull down on power-off and USB 2.0 descriptor modes. The EEPROM should be a 16 bit wide configuration such as a MicroChip 93LC46B or equivalent capable of a 1Mb/s clock rate at VCC = 4.35V to 5.25V, (FTDI, 2005).

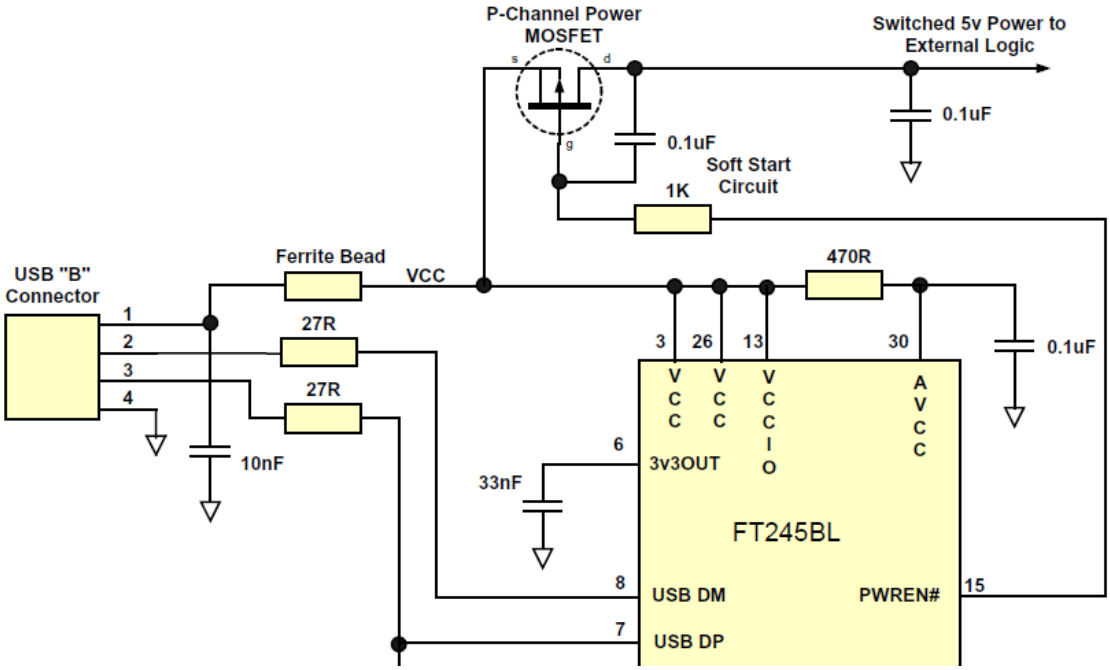


Figure 5.11: Wiring of the bus powered circuit with power control of the FT245

Microcontroller interface

Figure 5.12 illustrates a typical interface between the FT245BM and a microcontroller (MCU). This examples uses two IO Ports of the MCU, one port (8 bits) to transfer data and the other port (4/5 bits) to monitor the TXE# and RXF# status bits and generate the RD# and WR strobes to the FT245BM as required.

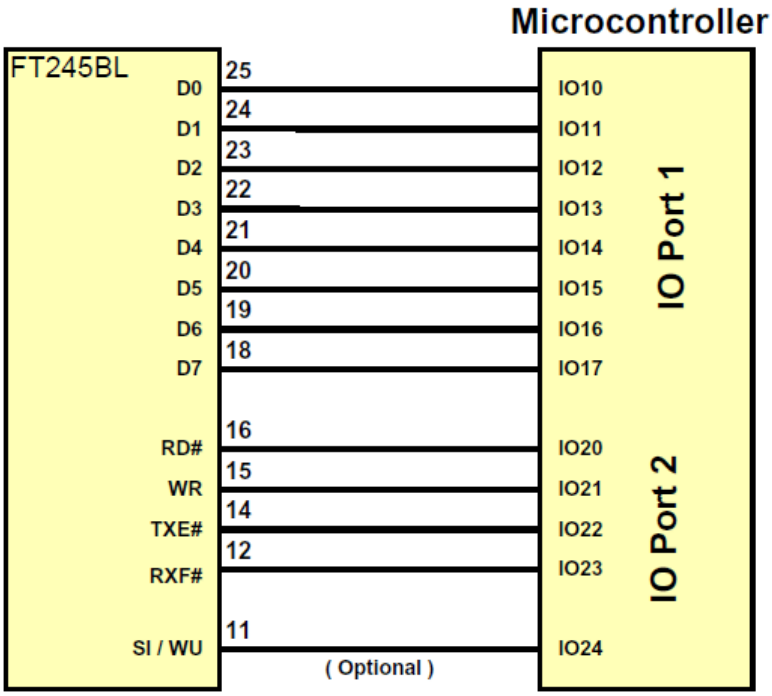


Figure 5.12: The interface between a microcontroller and the FT245

As the WR input of the FT245BM is not inverted but the WR output of the microcontroller is inverted a hex inverter 74AC04D is connected in between, (FTDI, 2005).

The overall schematic of all components is shown in figure 5.13.

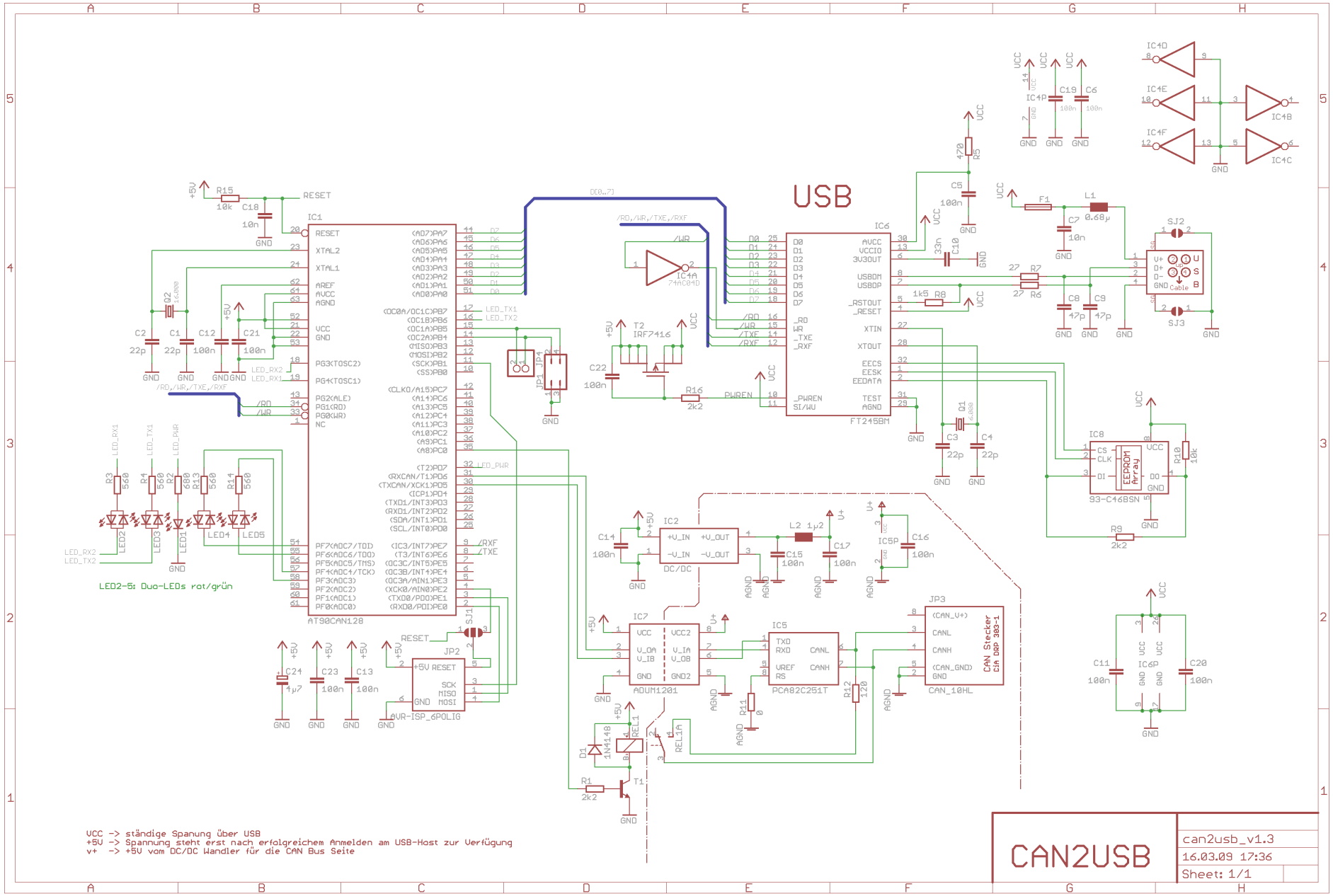


Figure 5.13: CAN circuit hardware layout

5.4. Hardware design of the new diagnostic device

The schematic in figure 5.13 is adjusted for a new diagnostic device prototype. The adjustments are as follows:

- The FT245BM is replaced with the VNC1L. The correct wiring of the VNC1L is provided by its datasheet. Two USB ports are designed in the layout. One servers as USB host and the other one as slave. This allows to connect a USB flash drive. The data for the memory drive are transmitted via the SPI interface of the microcontroller. The USB slave port enables an interface between the diagnostic device and a computer, which is especially helpful for the implementation of the developed diagnostic theory. In case of a specific CAN messages the tool should store diagnostic data on a USB flash drive which can be monitored by the connection to a computer at the same time. The CAN messages are transmitted to/from the computer in the same way shown in the CAN circuit using the parallel interface.
- The ISP header to the AT90CAN128 is replaced with headers for JTAG interface which is needed to implement the diagnostic theory.
- The power supply is changed as the old layout uses the power supplied by the USB connection of a computer. In the new layout the power supply of the car is used. Therefore a voltage regulator 7805 (IC3 in the layout) is used. The maximum rating for the 7805 are a DC input voltage of 35V. The car provides usually an input voltage of 12V. The output voltage of the 7805 is 5V and is the power supply of the AT90CAN128, the CAN transceiver and the hexinverter. The VNC1L needs an input voltage of 3.3V. Therefore a second voltage regulator MCP1700T3302 is used.
- For the port C of the AT90CAN128 a header interface is provided to connect a display for visual indication of faults.

The redesigned layout is shown in figure 5.14.

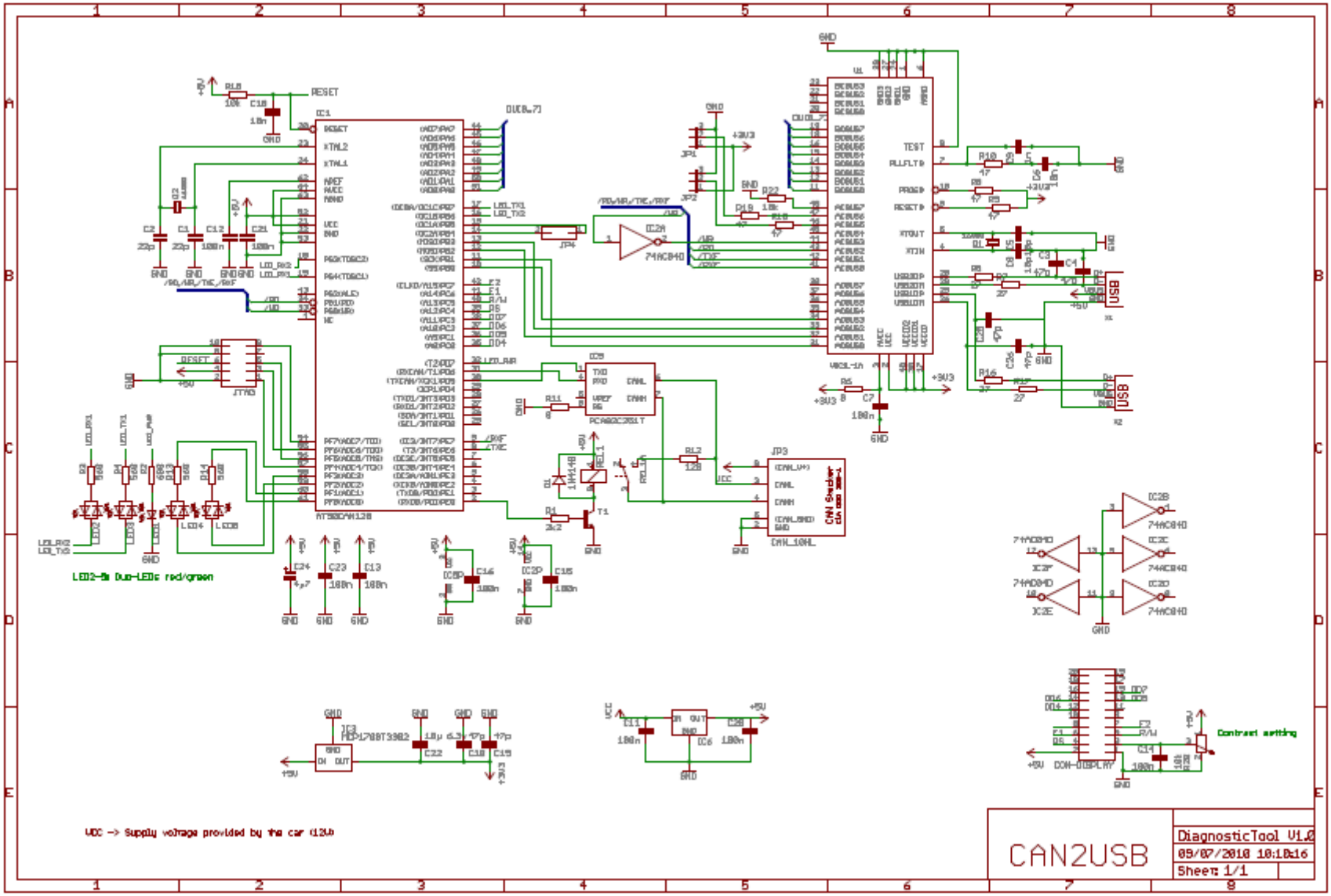


Figure 5.14: Diagnostic tool hardware layout

Chapter 6

Experimental Results

6.1. Results of the CAN circuit

The idea of the desired data flow of the CAN messages is shown in figure 6.1.

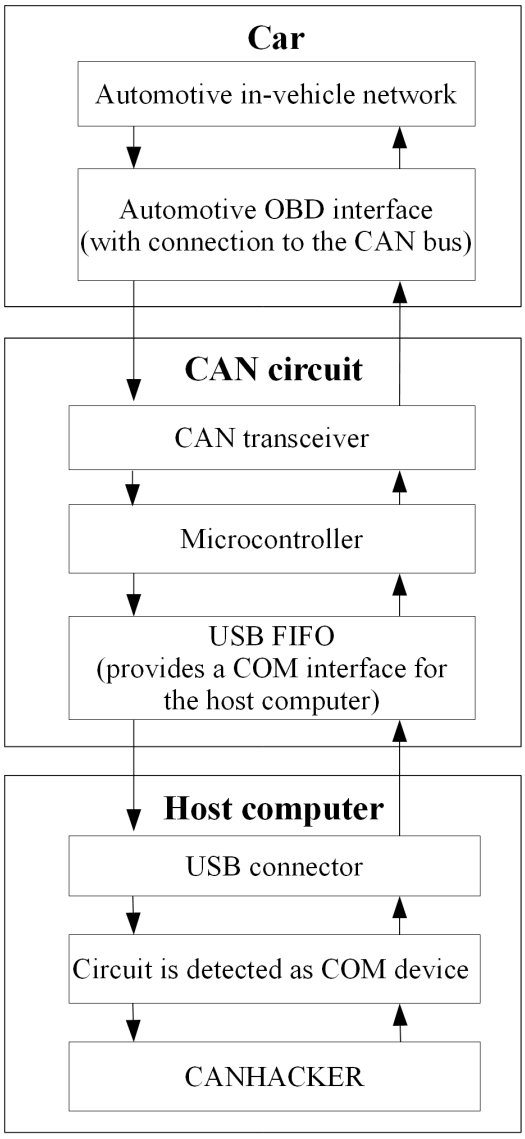


Figure 6.1: Data flow of CAN messages

The CAN circuit was connected to a Nissian Primera provided by the University of Huddersfield automotive lab using the OBD interface. The experimental setup is shown in figure 6.2.

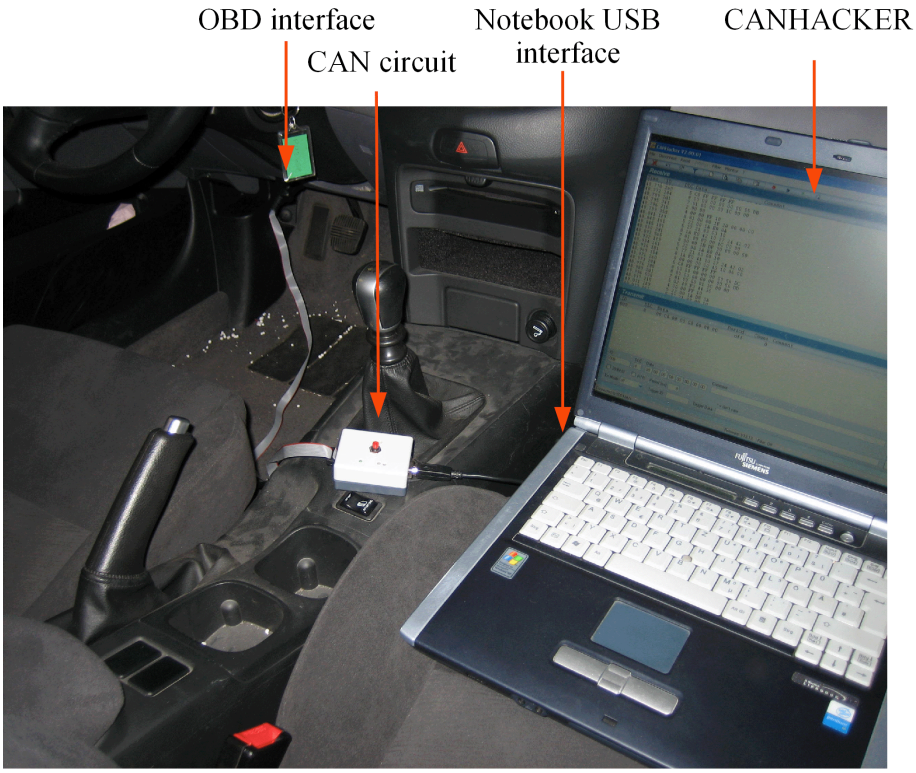


Figure 6.2: Experimental setup CAN circuit

As CAN monitor software the CANHACKER program was used. The program is free of costs and has following features:

- Fixed baud rates (10/20/50/100/ 125/250/500/800/1000bps);
- User defined baud rates;
- Identifier filter (Bit mask, single IDs, area of IDs);
- 11 bit identifier and 29 bit identifier;
- Listen only modus;
- Sending CAN messages;
- Automatic repeat of sending CAN messages;

- Replay of defined CAN messages;
- Storing received CAN messages;
- Adding comments on the CAN IDs;
- Display the message values in hex and decimal values;

In the settings menu the CAN interface must be selected choosing the used COM port. The baudrate of the COM port and the CAN bus can be adjusted in the settings menu as well.

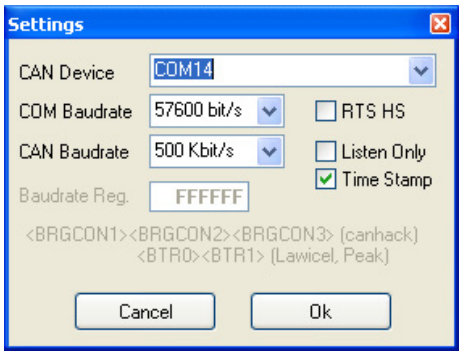


Figure 6.3: CANHACKER settings

After choosing the desired properties the CANHACKER connects to the CAN bus system of the car and is able to receive/transmit messages from/into the in-vehicle bus network. Figure 6.4 shows a screenshot of the CANHACKER receiving messages in an experimental test. In the transmit field own created messages can be send using the CAN ID.

It is possible to change the display mode from monitor to tracer. The monitor mode displays and counts the received messages while in tracer mode the received messages are displayed in chronological time order with a timestamp. Also the received and transmitted messages can be saved in a log file for further interpretation.

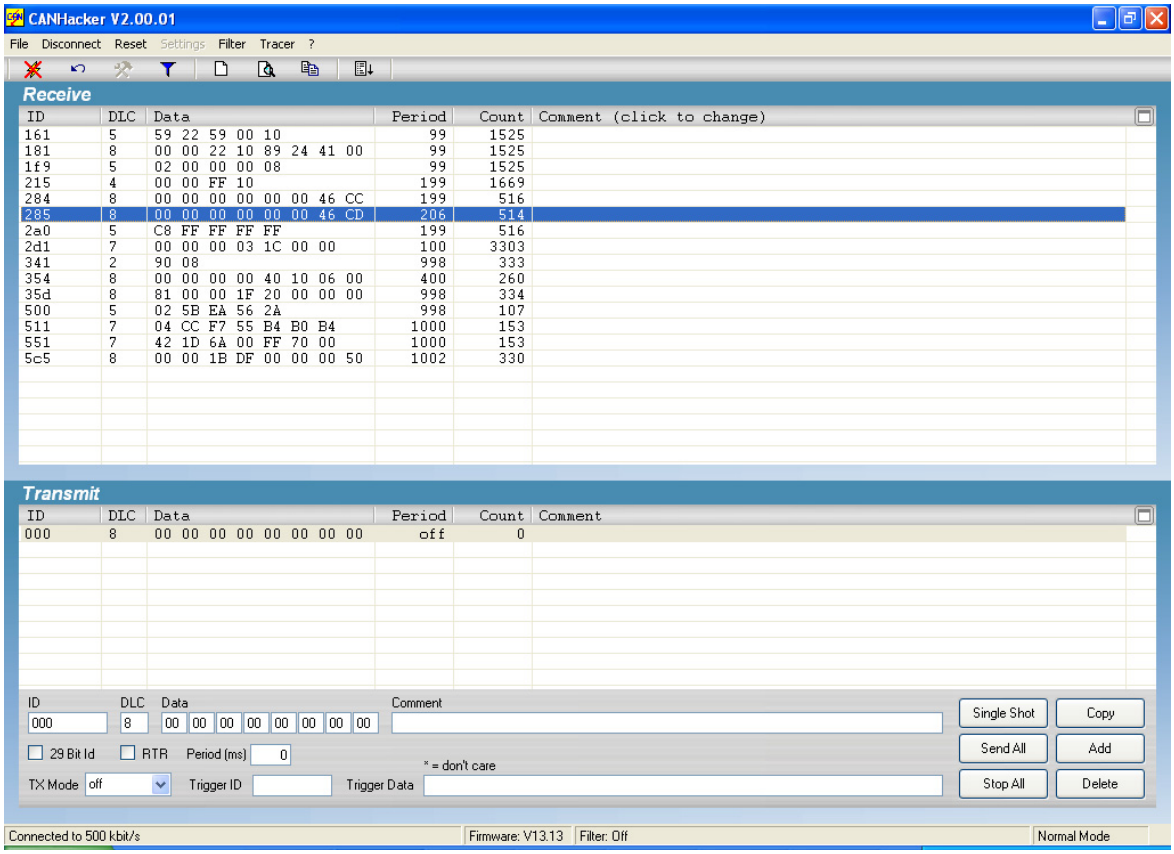


Figure 6.4: CANHACKER screenshot

A further function of the CANHACKER software is the filter shown in figure 6.5. The filter enables to receive only messages with a desired CAN ID. Applying the settings shown in the figure 6.5 results in receiving only messages with the CAN ID 215.

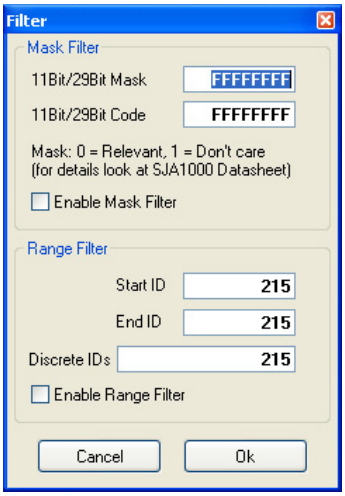


Figure 6.5: CANHACKER filter

The CAN bus level was recorded when the car was in idle mode and when the ignition was turned. Recording the CAN bus while driving was not possible because the car is not permitted to drive on roads. Also the car is standing on the 4 post ride simulator of the automotive engineering laboratory of the the University of Huddersfield!

To check the received data of correctness a professional tool for monitoring the CAN bus, the National Instrument PCMCIA-CAN card was connected to the bus system of the car. Figure 6.6 shows the configuration of the NI device.

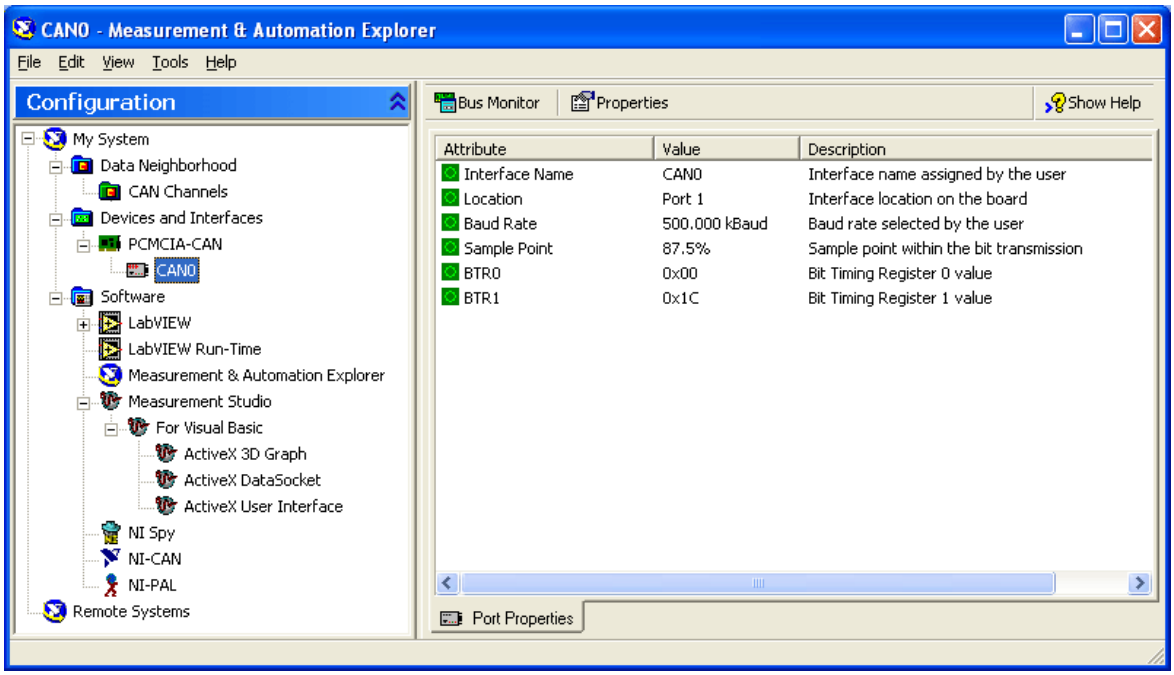


Figure 6.6: NI configuration

Similar to the CANHACKER software the properties of the used interface and baudrate can be adjusted shown in figure 6.7.

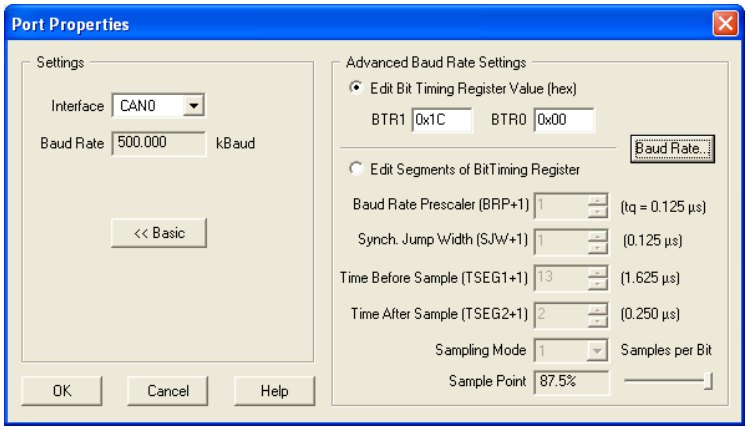


Figure 6.7: NI properties

The next figure 6.8 shows a screenshot of the recorded bus level when the ignition of the car was turned on.

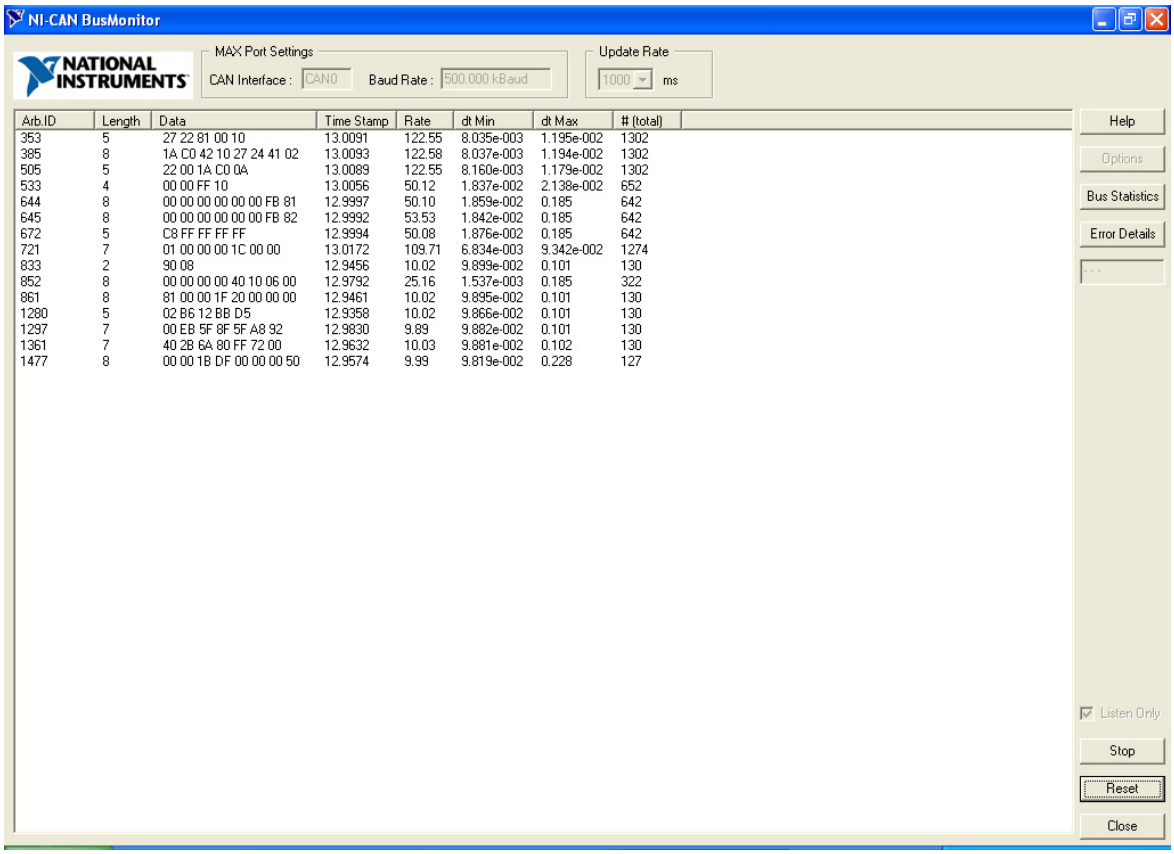


Figure 6.8: NI CAN BusMonitor screenshot

Comparing figure 6.4 and 6.8 shows that the recorded IDs with the NI tool and the own build CAN circuit are the same (IDs in figure 6.4 are in hex value). This proves that the CAN circuit is working.

6.2. Results of the new diagnostic device

The data flow between microcontroller, USB flash drive and display is shown in figure 6.9.

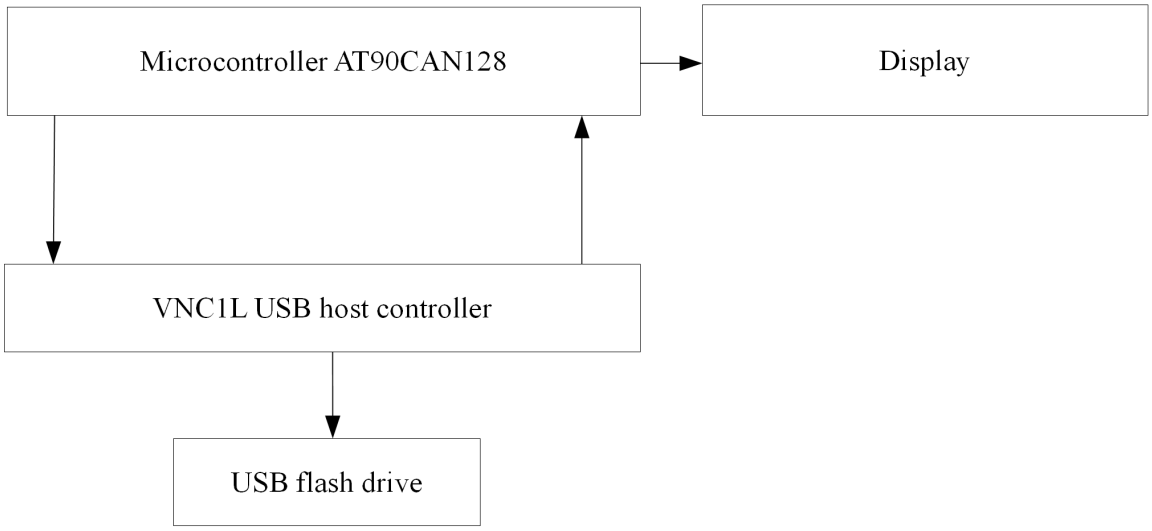


Figure 6.9: Data flow between microcontroller, USB flash drive and display

Therefore an interface for the VDIP1 module and the display was designed using headers to provide an easy connection to the STK600 board. The interface is shown in figure 6.10.

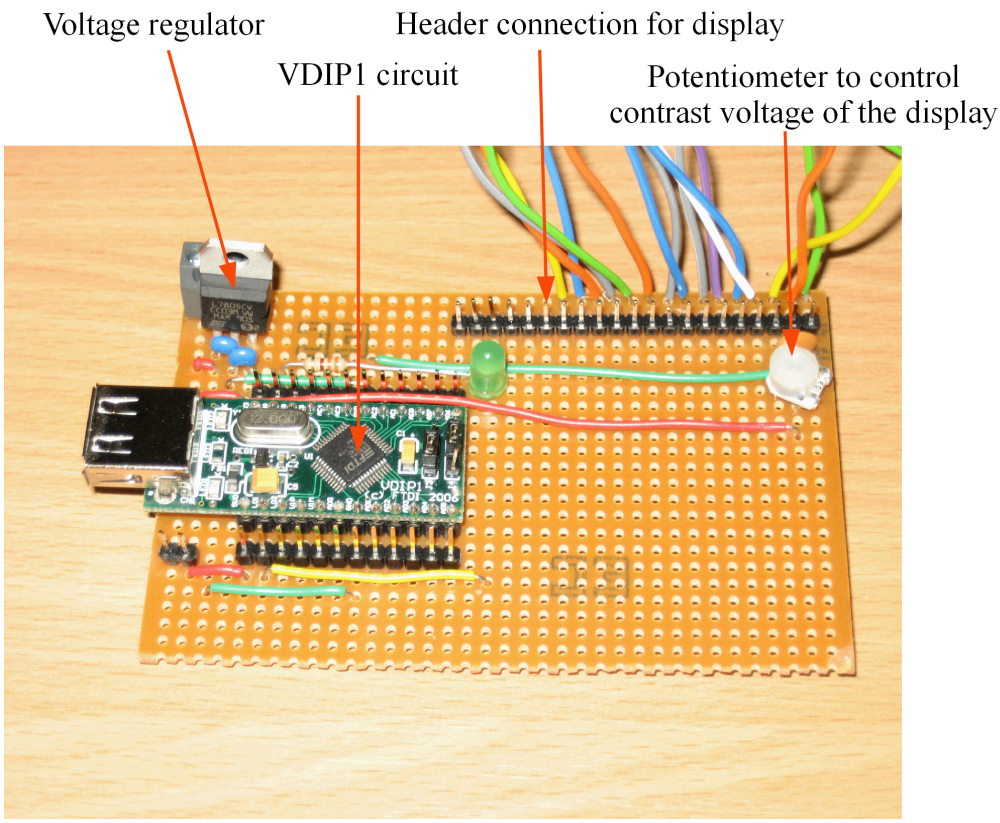


Figure 6.10: Interface for the VDIP1 module and the display

In figure 6.11 the connection of the experiment is shown. The STK600 is connected to the display and the VDIP1 module. For debugging purposes the JTAGICE mkII is connected to the STK600, too.

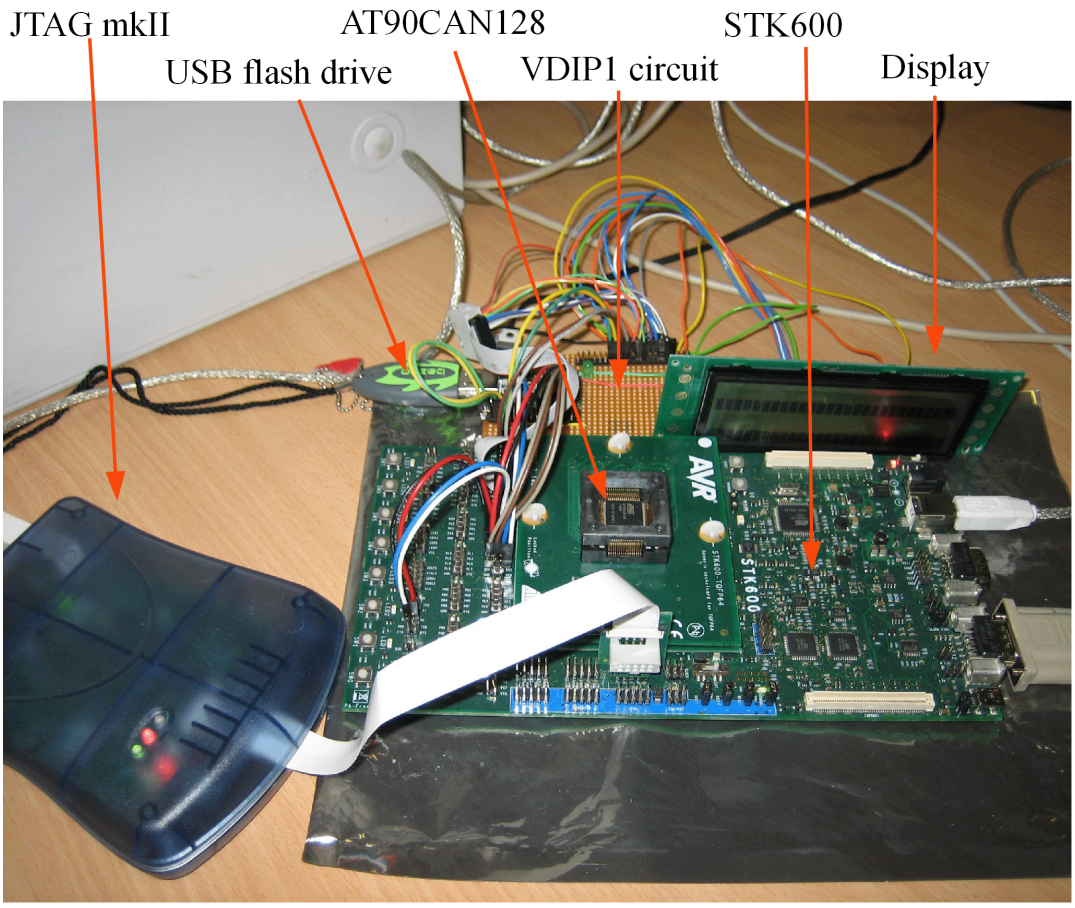


Figure 6.11: Experimental setup for USB flash drive and display

In the experiment a connection between the microcontroller AT90CAN128 and the USB memory flash drive as well as to the display (figure 6.11 shows the display in initialisation mode) was assembled. To test the connection a program which is published in the "Embedded Projects Journal" (Kahnt, 2009) was used. In the present experiment the AT90CAN128 wrote 3 test files on the memory flash drive which is shown in figure 6.12.

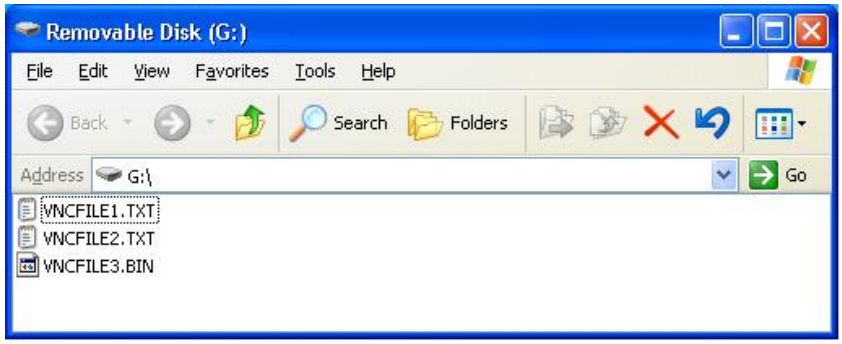


Figure 6.12: USB flahs drive screenshot

6.3. Future work for the hardware development

After showing that the CAN circuit, the connection between microcontroller and the USB host as well as to the display is working the future hardware design tasks of the new diagnostic device prototype are:

- Building the printed circuit board shown in figure 5.14.
- Merging the programs for the CAN circuit, the USB host and the display connection to a single program.
- Performing tests with the new build circuit with writing files on the USB flash drive on triggered CAN messages.

The desired data flow of CAN messages, storing and displaying data in the new onboard diagnostic device is shown in figure 6.13.

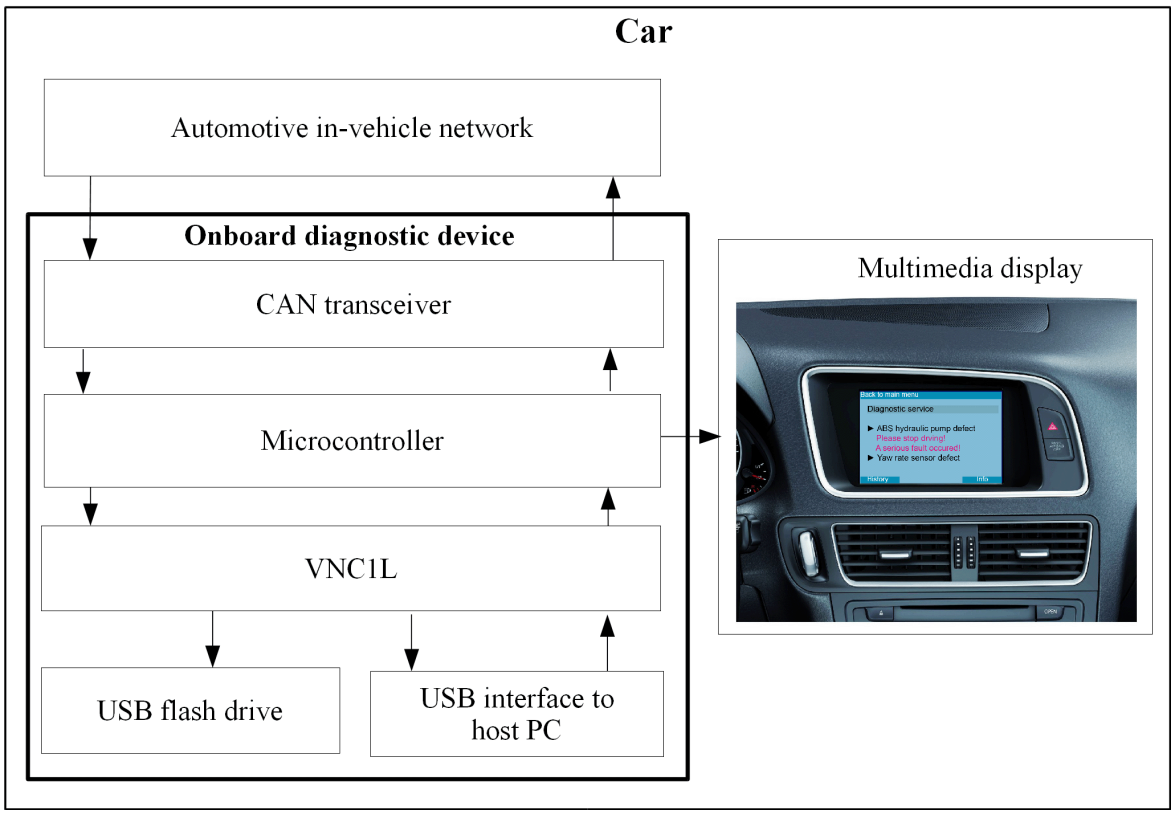


Figure 6.13: Data flow in the new diagnostic device

Chapter 7

Further Investigated Hardware Applications

7.1. Condition Monitoring of Mechatronic Car Components Using Bus Level Data Flow

The project idea "Condition Monitoring of Mechatronic Car Components Using Bus Level Data Flow" can be realized in the following steps:

Phase 1: Bus level experiments on different vehicles

- Recording the vehicle bus level on healthy car condition.
- Recording the vehicle bus level on faulty car condition.

Phase 2: Data analysis of the recorded bus level

- Interpretation of the bus level using the CAN matrix provided by the project partners (UAS Coburg, UAS Frankfurt am Main).
- The bus level changes between faultless and faulty condition.
- Merging the fault detection logic as a function of the bus level in error models.

If necessary it is possible to execute a hardware in the loop (HiL) simulation with single control units to obtain further and possibly more accurate data for the generation of the error models. Thereby the input signals of the controller are simulated and the output signals of the controller are fed back to the simulation. Thus allows an exact analyses of the controller behaviour on appearance of implausible/threshold input values.

Phase 3: Prototype establishment

Based on the error models it is now possible to build a prototype of the new onboard diagnostic tool. This is done by programming the fault model as functions in the previously built hardware. The CAN monitor is equipped with an LCD and a USB storage device to display and store data/messages in case of fault detection.

Phase 4: Prototype trail

The project can be completed with test results of the prototype. To validate the prototype test results a fault memory scanner, e.g. ELM327 can be used to compare diagnostic trouble code with detected faults of the developed prototype. Now it can be demonstrated whether it is possible to use the bus level for fault diagnosis or not.

The potential of this project is very high, due to the rapidly growing numbers of electronic parts in vehicles and the high error rate of such components shown previously in figure 1.2 and figure 1.4.

7.2. Tyre Pressure Control During a Vehicle Emergency Break

7.2.1. Introduction

4.154 people died on German roads in 2009 according to the preliminary data of the Federal Statistics Office, Germany. That means 7.2 % less people died compared to the figure of the year before which represents the lowest number since starting the recording in 1953. For comparison: 1953 the number of traffic deaths was 12.631 by 4.3 million licensed cars. The number of traffic deaths and licensed cars increased over the following years and in 1970 the mournful climax was reached with 21.322 traffic deaths and 20.8 million licensed cars. After this year the number of traffic deaths decreased continuously with little exceptions while the numbers of licensed cars increased. Figure 7.1 shows the context, (Statistisches Bundesamt Deutschland, 2009).

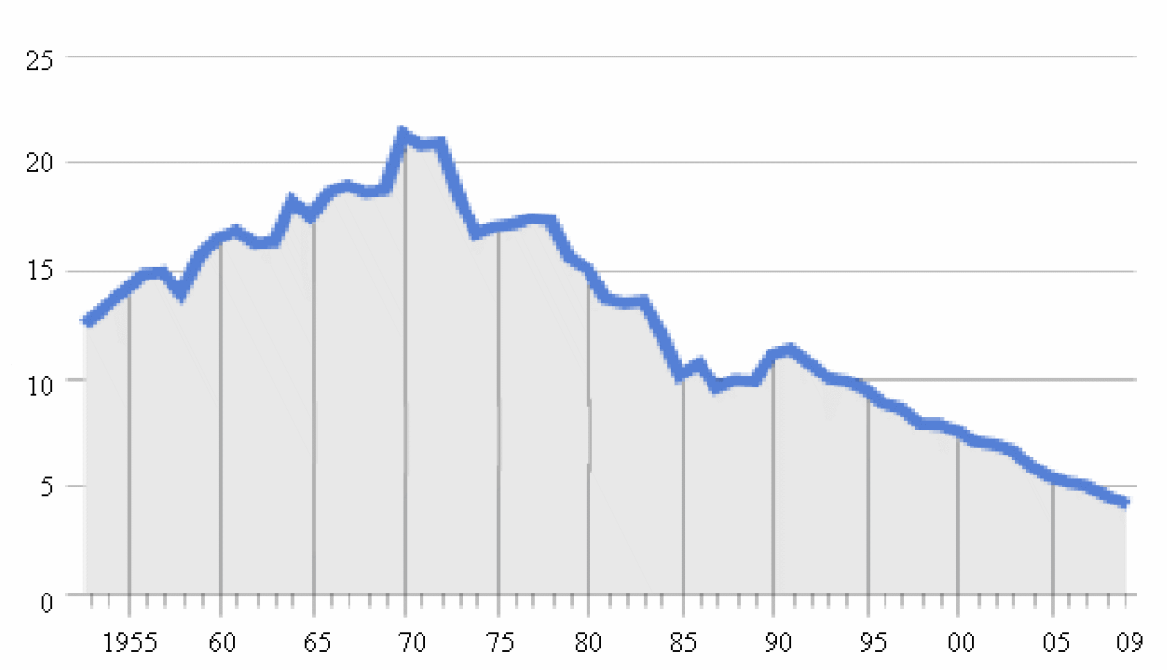


Figure 7.1: Road deaths in Germany over the last 54 years in thousands

In 2008 the reason for traffic accidents with injured persons was caused of circa 90% by driver misconducting. To face this point advanced driver assistance systems are integrated in cars. The aim of these systems is on the one hand to warn the driver against critical situation and on the other hand to assist the driver to handle a critical or dangerous situation. The reduction of traffic deaths in the last decades can be justified by the intensive use of such intelligent systems. In the next chapter the state of the art on the example of the Pre-Safe system developed by the Daimler AG and the ContiGuard system developed by the Continental AG is explained.

7.2.2. State of the art

In general it is differentiated in active safety systems to prevent accidents and passive systems to reduce the impact of a crash. An example for an active systems is the ABS while a seat belt tensioner represents the group of passive systems. Current developments in the automotive industry try to link active with passive system components which enables a complete event sequence beginning with the drivers warning of a critical situation till the automatic emergency call after an accident. Figure 7.2 shows a sequence of possible events, (Continental AG, 2010).

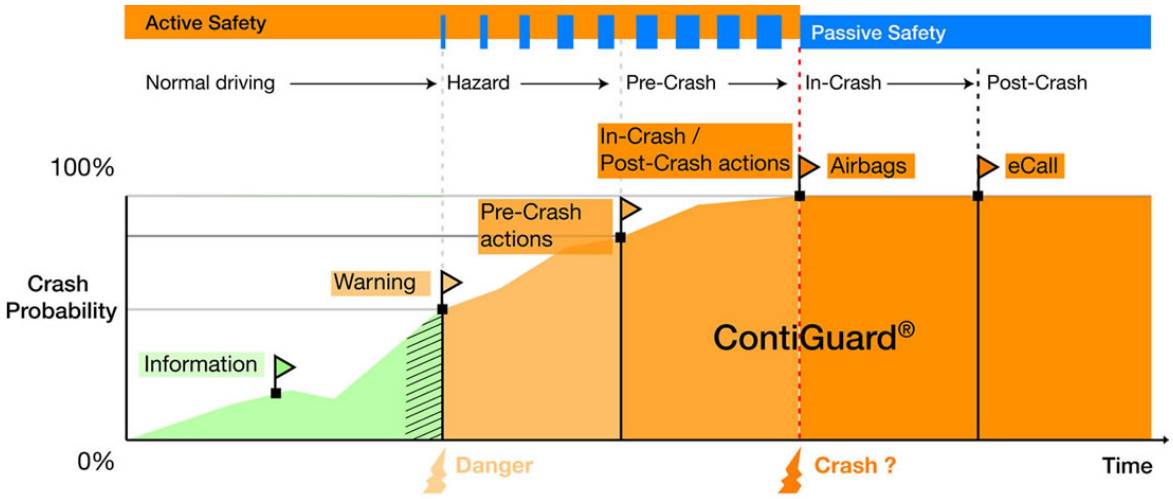


Figure 7.2: The sequence of possible events to reduce traffic deaths and injuries

In the year 2002 Mercedes Benz introduced the Pre-Safe system in the S-class, which detects a dangerous situation using the installed sensors of the car and initiates preventive measures:

- To increase the efficiency of the airbag the electric adjustable seats are forced into a collision optimized position.
- The side windows and whether existing, the sunroof, are closed to protect the vehicle passengers from entering objects.
- The electrical seat belt tensioner moves the passengers into a straight position.

The Pre-Safe system was extended with a radar device in the year 2005. The radar enables the system to warn the driver of a potential collision and to prepare the brake system for a possible emergency brake. In the following year the system was extended with an automatic emergency brake function. And for the first time the protection of other traffic participants was considered. An example is the automatic lifting of the engine bonnet in case of a collision between a car and a pedestrian.

To implement such complex functions in a highly linked safety system, many sensors and actuators as well as efficient communication systems are required:

- Beside the standard components of the ESC system a sensor for the distance measurement to other vehicles or objects is needed. Therefore radar systems are used in addition with diverse camera systems.
- Active actor components like seat belt tensioner, seat-, sunroof- and door control units were mentioned before. Further components are airbag control units and active steering systems.
- The communication of the participating components is carried out over the CAN bus of the car.

Figure 7.3 shows an overview of the APIA system components developed by the Continental AG, which is with its subsystem ContiGuard consistent to the Pre-Safe system, (Continental AG, 2010).

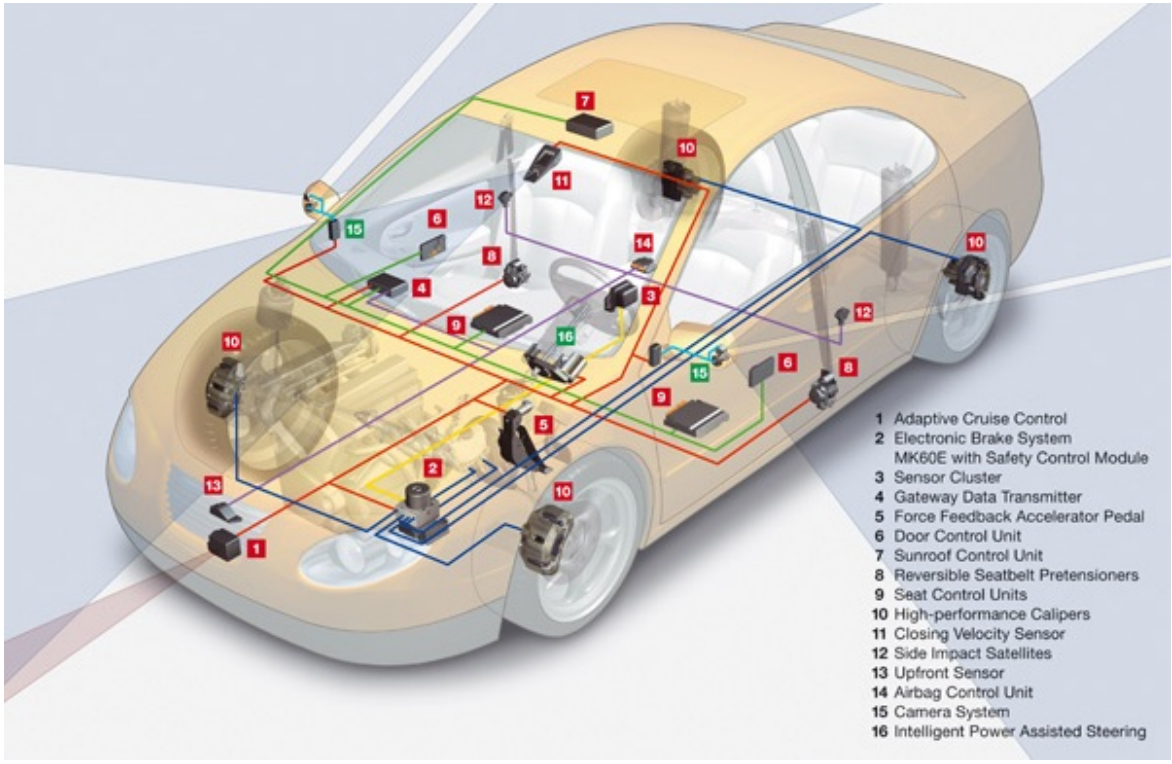


Figure 7.3: ContiGuard APIA system

After detecting a potential collision the system behaves as follows:

- Circa 2.6 seconds before a detected and calculated time of collision, the system warns the driver via optical and acoustic signals. Furthermore the driver is assisted as soon as he/she applies the brake according to the situation. The brake assistant calculates the optimal required braking pressure for the upcoming vehicle brake and fills the accumulator of the brake system appropriate.
- Circa 1.6 seconds before a potential collision: The driver has the optimal braking pressure as soon as he/she applies the brakes. The braking application is carried out with the optimal braking pressure independent of the used pedal force by the driver. However when the driver is not reacting to the warning signals an automatic partial braking is executed with a deceleration of up to 0.3 g. That is a deceleration of circa $3m/s^2$. Also passive safety systems inside the car are activated like the seat belt tensioner.
- 0.6 seconds before a potential collision: If the driver is not still reacting on the warning signals an automatic full braking with maximal braking force is carried out. This reduces the collision impact and stress for the vehicle passengers. The ADAC proved in road tests that the collision speed is reduced of 12.5 km/h achieved through an automatic emergency brake. That means a reduction of the stress for vehicle passengers of circa 30% for the front passengers and 45% for the passengers in the rear, (Daimler AG, 2010) .

In summary the systems on the market are marked by high complexity. Figure 7.3 shows the effort in the area of linked active and passive safety systems to realise the required functions. The biggest benefit of the linking is the availability of various information, which are distributed over the whole vehicle. Through monitoring and analysing the data flow in the car it is possible to use the existing information for implementing new functions. This approach is the basis of this research project which is explained in the next chapter.

7.2.3. Aims and objectives of the project

The aim of the project “Tyre Pressure Control During a Vehicle Emergency Break” is a reduction of the collision speed and therefore a further reduction of the stress and the resulting injuries for vehicle passengers.

The available systems on the market described in the previous chapter shows, that the real contact point of the braking force, the area of contact between tyre and road surface is unconsidered. The physical process in the contact area, called tyre contact patch is extremely complicated and is described by the physical phenomena of rubber friction. The rubber friction is a combination of adhesive, cohesive and viscous friction as well as hysteresis. On dry road surface the adhesive friction is dominant. Detailed analyses of this phenomena shows that the adhesive friction depends mainly on the rubber material, but also on the contact area size. At this point the rubber friction differs significant from the friction between two solid objects where the friction is independent of the contact area. Following the adhesive friction characteristic means increasing the tyre contact patch reduces the braking distance. Enlarging the tyre contact patch can be achieved by dropping the tyre pressure.

The aim of the project is the development of a mechatronic control system, which recognises immediately a near emergency brake by analysing the bus communication of the car and executes an autonomous systematic dropping of the tyre pressure.

The following components have to be developed:

- An electronic control unit with an interface to the CAN bus.
- A tyre valve, which allows a dynamic dropping of the tyre pressure in case of an emergency brake.
- A wireless communication interface between the control unit and tyre valve.

The next chapter describes the requirements of the subsystems in detail and explains the development methods.

7.2.4. Realisation of the project idea

To realise a mechatronic system for tyre pressure control in case of an emergency brake diverse development-, simulation-, test- and assembling tasks must be carried out. The following informs about the individual subprojects including the tasks in the area of mechanics and electronics as well as of control engineering and software development.

- Development of the electronic control unit (ECU): This subsystem is the central unit of the whole system. One task of the ECU is to communicate to other vehicle components and the analysis of the signals on the CAN bus. The ECU can conclude an occurrence of an automatic emergency break and controls the tyre valves as needed. Therefore the control unit needs an interface to the vehicle communication system and a second wireless interface to communicate with the actuators on the tyre valves. As basis the developed CAN bus interface on the AT90CAN128 microcontroller can be used, described in this thesis. The wireless interface will use the ZigBee standard. The development needs a special focus on the fail safe of the system. Because systems with autonomous influence on the vehicle driving dynamics have special requirements by law. In particular the system needs to be redundant, which means build up with two independent microcontrollers. The hardware design can be carried out with the program Eagle which was also used for the development of the CAN monitor.
- Construction of a mechatronic tyre valve: The tyre valve is controlled by the ECU using a wireless interface and enables to release tyre pressure as much as needed. A specific challenge is the position of the tyre valve, normally on the tyre outside which requires a compact and robust design. Furthermore this subsystem needs to measure the current tyre condition, e.g. the tyre pressure. The mechatronic tyre is currently under development with integrated sensors and communication interfaces. As example the European research projects Apollo and FRICTI@N are to mention. Results of Apollo and FRICTI@N will be considered in this project, (Apollo, 2005), (FRICTI@N, 2009).
- Development of the control algorithm: For the control software development of the mechatronic tyre valve modern tools and simulation techniques are used. An

industrial standard for the implementation of such complex systems is the rapid prototyping method with fast real time simulation. Firstly a mathematical-physical vehicle-tyre-road system has to be modelled. The created model is transformed in a computer based simulation environment which allows to test different control strategies with development tools. The achieved control algorithm can be implemented on real time capable computers per mouse click and controls the connected hardware. The extensive programming in a high level language like C in the development- and assembling stage is not required. After finishing the development the rapid prototyping system enables an autonomous generation of C-code which can be flashed on the target hardware of the ECU.

7.3. Automotive security analysis

The University of Washington and the University of California San Diego presented the paper “Experimental Security Analyses of a Modern Automobile” at the IEEE Symposium on Security and Privacy in Oakland the 19th of May 2010. In the paper the issues of new potential risks are experimentally evaluated, caused by the implementation of electronic control units in cars. Furthermore an attack to infiltrate the behaviour of the control unit is demonstrated.

The experiment was carried out in three principle settings:

- A bench test with the physical extracted hardware (ECUs) from the car.
- A stationary car test on jack stands using the OBD connector to get access to the internal bus system of the car. As hardware was an Olimex AVR-CAN development board with an AT90CAN128 used. The software interface CARSHARK is self developed to receive and send CAN messages in the CAN network, which is similar to the CANHACKER program described earlier in this thesis.
- An on road test using a de-commissioned airport runway.

The paper points out that the communication between a tester and the ECU is encrypted with 16 bits and a hacker can crack the key in seven and a half days. The research team

removed the electronic brake control module and decrypted the key in one and a half day which enables a control unit reflashing for example.

The diagnostic protocol standard prescribes strategies to mitigate risks. But the experiment showed that not all components are following the specifications:

- A communication between test device and the ECU has to be disabled while the car is driving.
- A reflashing of the ECU has to be rejected if the engine is running. But this was possible in the performed experiment. While driving the car the engine control module and the transmission control module were reflashed.

The attacks were carried out after the following methodology:

- Packet sniffing and target probing to reveal where packets are sent to activate various components (e.g. turning on the headlights). This approach is helpful to probe packets during normal driving but is not useful for mapping the interface of safety critical components.
- Fuzzing sends automatically random created messages in the network to probe the meaning of CAN messages. Also the car used for the experiment defines a CAN based service called DeviceControl, which allows test devices to override the normal output functionality of an ECU. This device is used during the quality control of the manufacturing process. The DeviceControl functions were discovered by fuzz testing.
- Reverse engineering was applied to read the ECU code with the *ReadMemory* service. A third party debugger was used to understand how the hardware features are controlled and manipulated by the software with removing or adding new functions.

The table (appendix G) shows the results of the experiment. The first column shows the packet which was sent and the result is explained in the next column. Manual override means if the result of the package can be overridden manually, e.g. pushing the brakes or by pulling the physical door unlock knob. The “At Speed” column shows if the packet has

the same effect when the car is at speed. The column “Need to Unlock” indicates if the control unit needs to be unlocked with its DeviceControl key to react on the received message. And the last column shows if this experiment was carried out on a runway as well, (Koscher K. et al., 2010).

Chapter 8

Conclusion

In this research project all objectives are achieved and can be claimed as successful:

Objective 1: Investigation of the historical and current concepts used for automobiles diagnostics.

Achievement: As shown in the thesis a deep understanding in the areas of automotive electrical systems, control systems, the cross linking of mechatronic systems and the used diagnostic concepts is gained. Also the author increased his knowledge in the areas of microcontroller and hardware development.

Objective 2: Development of an advanced diagnostic approach.

Achievement: A new idea for an advanced diagnostic approach has been developed. The potential of the idea is high in aspects of realisation, business market and the ability of a patent. Also the idea can be published for conferences and in journal papers.

Objective 3: Design the hardware of a prototype diagnostic tool using the new developed approach.

Achievement: An interface to analyse the communication is built and can be used for different tasks shown in this thesis. The extension with a USB host and a display of the communication to a new onboard diagnostic tool can be published for conferences and in journal papers.

Further achievements:

- An idea of a new automotive passive safety system has been developed and can be carried out in a future project. The new safety system which controls the tyre pressure during a vehicle emergency brake has big potential to reduce the stress for vehicle passengers in case of a collision. The market potential can be claimed as high and the system has to be protected by a patent.

- The mentioned automotive security analysis in this thesis shows that the University of Huddersfield is up to date in the field of automotive electrics and has gained new knowledge and experience from this research project, allowing the continuation of further research projects in the field of automotive electronics e.g. in the fields of diagnostics, control systems and security analysis.

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Appendices

Appendix A: Unified diagnostic services

Service Name	SID	Former SID in KWP 2000	LEV 6....0	Parameter/Comments	Mnemonic	Availability in Default Session	Functional Class
Diagnostic Session Control	10h	10h	01h 02h 03h 40h - 7Eh	Start a Diagnostic Session Default Session Programming Session Extended Diagnostic Session Manufacturer specific Session	DSC	Yes	Diagnostic and Communication Management
ECU Reset	11h	11h	01h 02h 04h 40h-7Eh	Hard reset Ignition on – ignition off Soft reset Manufacturer specific reset sequences	ER	Yes	
Security Access	27h	27h	01h 02h ...	Request Seed Send Key Manufacturer specific values	SA		
Communication Control	28h	28h, 29h	...	The tester can prompt to cancel sending and/or receiving messages of the control unit from other control unit in the network.	CC		
Tester Present	3Eh	3Eh		Keep alive message to hold the connection, while no other diagnostic messages are present.	TP	Yes	
Access Timing Parameter	83h	83h	01h 02h 03h 04h	Reading and setting the timing parameters of the control unit, which are depending on the used bus system Read the supplied values of the control unit Reset to default values Read the current set values	ATP		

				Set new timing parameters			
Secured Data Transmission	84h	New		Encryption and decryption of the data after ISO 15764.	SDT		
Control DTC Setting	85h	85h	...	The tester can prompt the control unit to enable or disable of storing trouble codes. This is useful when the garage has to perform an actor test or replace wires.	CDTCS		
Response on Event	86h	New	00h 01h 02h 03h 04h 05h 06h 07h	Stop Response on Event On DTC Status Change On Timer Interrupt On Change of Data Identifier One or more events installed Start Response on Event Clear Response on Event On Comparison of Values	ROE	Yes	
Link Control	87h	New	...	Change the bit rate	LC		
Read Data By Identifier	22h	21h, 22h Single	-	Single reading of control unit data	RDBI	Yes	Data Transmission
Read Memory By Address	23h	23h Single	-		RMBA	Yes	
Read Scaling Data By Identifier	24h	New	-		RSDBI	Yes	
Read Data By Periodic Identifier	2Ah	21h, 22h Periodic	01h 02h 03h 04h	Periodical reading of control unite data. Sending with a low bit rate Sending with an average bit rate Sending with a high bit rate Stop sending	RDBPI		
Dynamically Define Data Identifier	2Ch	2Ch	01h 02h	Dynamic compilation of data to a dataset and allocation of a code number. Choice from an existing dataset	DDDI	Yes	

			03h	Choice by memory address Erasing code number			
Write Data By Identifier	2Eh	2Eh, 3Bh	-	Writing data in the flash of the control unit.	WDBI	Yes	
Write Memory By Address	3Dh	3Dh	-		WMBA	Yes	
Clear Diagnostic Information	14h	14h		Erase complete fault memory	CD	Yes	Transmission of stored data
Read DTC Information	19h	12h, 13h, 17h, 18h	0Ah 01h 02h 07h – 09h 12h 13h 0Bh – 0Eh 03h – 06h 0Fh - 11h	Listing all possible DTC with status information Number and list of DTCs with a specific trouble mask Number and list of DTCs with a specific trouble border Number and list of all OBD relevant faults Read newest and oldest fault entry Read environment conditions Read error from fault memory	RDTCI	Yes	
Input Output Control By Identifier	2Fh	2Fh, 30h	-	Overwrite a control unit input or direct actuation a control unit output.	IOCBI		In- and Output Control
Routine Control	31h	31h, (38h) 32h,(39h) 33h, (3Ah)	01h 02h 03h	Execution of routines Start Stop Polling of events	RC	Yes	Remote Function Control
Request Download	34h	34h	-		RD		Transmission of flash memory data
Request Upload	35h	35h	-		RU		
Transfer Data	36h	36h	-		TD		
Request Transfer Exit	37h	37h	-		RTE		

Appendix B: OBD services

Service	SID	Comments and PIDs
Fault memory		
Request emission related diagnostic trouble codes	03h	Only finally detected errors are reported. No PID.
Request emission related diagnostic trouble codes detected during current or last completed driving cycle	07h	Report of all errors, including temporary faults. No PID.
Request powertrain freeze frame data	02h	Request of environment data of an error.
Clear emission related diagnostic information	04h	Erasing the fault memory which includes trouble codes, environment data and status of sundry tests. No PID.
Test emission related components		
Request oxygen sensor monitoring test results	05h	Monitoring the lampda sensor.
Request on board monitoring test results for non continuously monitored systems	06h	Monitoring the catalyst, exhaust recuperations, probe and catalyst heating, ignition and injector systems.
Request control of on board system, test or component	08h	Check of tank ventilation.
Read control unit values		
Request current powertrain diagnostic data	01h	Request of control unit data values, which is selected over specific PIDs. This command is also possible while driving the car to localise the fault.
Request vehicle information	09h	Reading of the vehicle identification number (PID = 02h), calibration identification (PID = 04h), calibration verification number (PID = 06h).
	0A-0Fh	Reserved

Appendix C: Range of values

PID	Meaning	Data size	Range (min...max)
04h	Engine load	8 bit	0 ...100 %
05h	Cooling water temperature	8 bit	- 40 ... + 215 °C
06h...09h	Fuel quantity correction of the injection valves (for 2 cylinders)	8 bit	- 100 ... + 99.2 %
0Bh	Pressure in the inlet manifold	8 bit	0 ... 255 kPa
0Ch	Engine RPM	16 bit	0 ... 16383.75 1/min
0Dh	Vehicle speed	16 bit	0 ... 255 km/h
0Eh	Ignition angle (for cylinder 1)	8 bit	- 64 ... +63.5 °
0Fh	Inlet air temperature	8 bit	- 40 ... +215 °C
10h	Air mass	16 bit	0 ... 655.35 g/s
11h	Acceleration pedal position	8 bit	0 ... 100 %
14h...1Bh	Oxygen sensor voltage (PID = 24h ... 2Bh or 34h ... 3Bh depending on sensor type)	8 bit (16 bit)	0 ... 1.275 V
2Ch	Exhaust gas recirculation rate	8 bit	0 ... 100%
31h	Driving distance since erasing the fault memory	16 bit	0 ... 65535 km
4Eh	Operating time since erasing the fault memory	16 bit	0 ... 65535 min
21h	Driving distance since turned on MIL	16 bit	0 ... 65535 km
4Dh	Operating time of since turned on MIL	16 bit	0 ... 65535 min

Appendix D: AT90CAN128 pin description

Pin #	Signal	Type	Description
21, 52	VCC	Power	Digital supply voltage
22, 53, 63	GND	Power	Ground
44 - 51	PA7...PA0	I/O	8-bit bi-directional I/O port with internal pull-up resistors (selected for each bit).
10 -17	PB7...PB0	I/O	8-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). This port also serves the functions of various special features of the AT90CAN128.
35 - 42	PC7...PC0	I/O	8-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). This port also serves the functions of various special features of the AT90CAN128.
25 - 32	PD7...PD0	I/O	8-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). This port also serves the functions of various special features of the AT90CAN128.
2 - 9	PE7...PE0	I/O	8-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). This port also serves the functions of various special features of the AT90CAN128.
54 - 61	PF7...PF0	I/O	Port F serves as the analogue inputs to the A/D Converter. also serves as an 8-bit bi-directional I/O port, if the A/D Converter is not used. Port pins can provide internal pull-up

			resistors (selected for each bit). This port also serves the functions of various special features of the AT90CAN128.
18, 19, 33, 34, 43	PG4...PG0	I/O	5-bit I/O port with internal pull-up resistors (selected for each bit). This port also serves the functions of various special features of the AT90CAN128.
20	$\overline{\text{RESET}}$	In	Reset input. A low level on this pin for longer than the minimum pulse length will generate a reset.
23	XTAL1	In	Input to the inverting Oscillator amplifier and input to the internal clock operating circuit.
24	XTAL2	Out	Output from the inverting Oscillator amplifier.
64	AVCC	Power	AVCC is the supply voltage pin for the A/D Converter on Port F.
62	AREF	Power	Analogue reference pin for the A/D Converter.

Appendix E: FT245 pin description

Pin #	Signal	Type	Description
1	EESK	Out	Clock Signal to EEPROM.
2	EEDATA	I/O	EEPROM – Data I/O.
3, 26	VCC	Power	VCC to the device core.
4	RESET#	In	Can be used by an external device to reset the FT245BL.
5	RSTOUT#	Out	Output of the internal reset generator.
6	3V3OUT	Out	3.3 volt output from the integrated low dropout regulator.
7	USBDP	I/O	USB data signal plus.
8	USBDM	I/O	USB data signal minus.
9, 17	GND	Power	Device - ground supply pins.
10	PWREN#	Out	Goes low after the device is configured via USB, then high during USB suspend.
11	SI / WU	In	The Send Immediate / WakeUp signal combines two functions on a single pin. If USB is in suspend mode (PWREN# = 1) and remote wakeup is enabled in the EEPROM , strobing this pin low will cause the device to request a resume on the USB Bus. Normally, this can be used to wake up the host PC. During normal operation (PWREN# = 0), if this pin is strobed low any data in the device TX buffer will be sent out over USB on the next Bulk-IN request from the drivers regardless of the pending packet size.
12	RXF#	Out	When high, do not read data from the FIFO. When low, there is data available in the FIFO which can be read by strobing RD# low then high again.
13	VCCIO	Power	VCC to the FIFO interface pins 10..12, 14..16 and 18..25.
14	TXF#	Out	When high, do not write data into the FIFO. When low, data can be written into the FIFO by strobing WR high then low.
15	WR	In	Writes the data byte on the D0...D7 into the transmit FIFO buffer when WR goes from high to low.
16	RD#	In	Enables current FIFO data byte on D0...D7 when low. Fetches the next FIFO data byte (if available) from the

			receive FIFO buffer when RD# goes from low to high.
18	D7	I/O	FIFO Data Bus Bit 7.
19	D6	I/O	FIFO Data Bus Bit 6.
20	D5	I/O	FIFO Data Bus Bit 5.
21	D4	I/O	FIFO Data Bus Bit 4.
22	D3	I/O	FIFO Data Bus Bit 3.
23	D2	I/O	FIFO Data Bus Bit 2.
24	D1	I/O	FIFO Data Bus Bit 1.
25	D0	I/O	FIFO Data Bus Bit 0.
27	XTIN	In	Input to 6MHz crystal oscillator cell.
28	XTOUT	Out	Output from 6MHz crystal oscillator cell.
29	AGND	Power	Device - analogue ground for the internal x8 clock multiplier.
30	AVCC	Power	Device - analogue power supply for the internal x8 clock multiplier.
31	TEST	In	Puts device in integrated circuit test mode.
32	EECS	I/O	EEPROM – Chip Select.

Appendix F: VN1CL pin description

Pin#	Signal	Type	Description
1, 24, 27, 39	GND	Power	Device ground supply pins.
2	VCC	Power	+3.3V supply to the device core.
3	AVCC	Power	+3.3V supply to the internal clock multiplier. This pin requires a 100nF decoupling capacitor.
6	AGND	Power	Device analogue ground supply for internal clock multiplier.
17, 30, 40	VCCIO	Power	+3.3V supply to the ADBUS, ACBUS, BDBUS and BCBUS Interface pins (11..16, 18..23, 31..38, 41..48). Leaving the VCCIO unconnected will lead to unpredictable operation on these interface pins.
4	XTIN	In	Input to 12MHz Oscillator Cell. Connect 12MHz crystal across pins 4 and 5, with suitable loading capacitors to GND. This pin can also be driven by an external 12MHz clock signal. Note that the switching threshold of this pin is VCC/2, so if driving from an external source, the source must be driving at +3.3V CMOS level or AC coupled to centre around VCC/2.
5	XTOUT	Out	Output from 12MHz Oscillator Cell. Connect 12MHz crystal across pins 4 and 5, with suitable loading capacitors to GND. XTOUT stops oscillating during USB suspend, so take care using this signal to clock external logic.
7	PLLFLTR	In	External PLL filter circuit input. RC filter circuit must be fitted on this pin.
8	TEST	In	Puts the device into IC test mode. Must be tied to GND for normal operation.

9	RESET#	In	Can be used by an external device to reset VNC1L. This pin can be used in combination with PROG# and the UART interface to program firmware into VNC1L. If not required pull-up to VCC via a 47kΩ resistor.			
10	PROG#	In	This pin is used in combination with the RESET# pin and the UART interface to program firmware into VNC1L.			
11 ... 19	BDBUS0 ... 7	I/O	5V safe bidirectional data/control bus, BD bit 0 ... 7.			
20 ... 23	BCBUS0 ... 3	I/O	5V safe bidirectional data/control bus, BC bit 0 ... 3.			
25	USB1DP	I/O	USB host/slave port 1 - USB Data Signal Plus with integrated pull-up/pull-down resistor.			
26	USB1DM	I/O	USB host/slave port 1 - USB Data Signal Minus with integrated pull-up/pull-down resistor.			
28	USB2DP	I/O	USB host/slave port 2 - USB Data Signal Plus with integrated pull-up/pull-down resistor.			
29	USB2DM	I/O	USB host/slave port 2 - USB Data Signal Minus with integrated pull-up/pull-down resistor.			
Pin#	Signal	Type	Description	UART interface	Parallel FIFO interface	SPI slave interface
31	ADBUS0	I/O	5V safe bidirectional data/control bus, AD bit 0	TXD	D0	SCLK
32	ADBUS1	I/O	AD bit 1	RXD	D1	SDI
33	ADBUS2	I/O	AD bit 2	RTS#	D2	SDO
34	ADBUS3	I/O	AD bit 3	CTS#	D3	CS
35	ADBUS4	I/O	AD bit 4	DATAACK#	D4	
36	ADBUS5	I/O	AD bit 5	DATAR	D5	

				EQ#		
37	ADBUS6	I/O	AD bit 6	DCD#	D6	
38	ADBUS7	I/O	AD bit 7	RI#	D7	
41	ACBUS0	I/O	5V safe bidirectional data/control bus, AC bit 0	TXDEN#	RXF#	
42	ACBUS1	I/O	AC bit 1		TXE#	
43	ACBUS2	I/O	AC bit 2		RD#	
44	ACBUS3	I/O	AC bit 3		WR	
45	ACBUS4	I/O	AC bit 4		DATAREQ#	DATAREQ#
46	ACBUS5	I/O	AC bit 5		DATAACK#	DATAACK#
47/48	ACBUS6/7	I/O	AC bit 6/7			

Appendix G: Automotive security

Packet	Result	Manual Override	At Speed	Need to Unlock	Tested on Runway
Body Control Module DeviceControl Packet Analysis					
07 AE ... 1F 87	Continuously Activates Lock Relay	Yes	Yes	No	Yes
07 AE ... C1 A8	Windshield Wipers On Continuously	No	Yes	No	Yes
07 AE ... 77 09	Pops Trunk	No	Yes	No	Yes
07 AE ... 80 1B	Releases Shift Lock Solenoid	No	Yes	No	
07 AE ... D8 7D	Unlocks All Doors	Yes	Yes	No	
07 AE ... 9A F2	Permanently Activates Horn	No	Yes	No	Yes
07 AE ... CE 26	Disables Headlights in Auto Light Control	Yes	Yes	No	Yes
07 AE ... 34 5F	All Auxiliary Lights Off	No	Yes	No	
07 AE ... F9 46	Disables Window and Key Lock Relays	No	Yes	No	
07 AE ... F8 2C	Windshield Fluid Shoots Continuously	No	Yes	No	Yes
07 AE ... 15 A2	Controls Horn Frequency	No	Yes	No	
07 AE ... 22 7A	Controls Instrument Brightness	No	Yes	No	
07 AE ... 00 00	All Brake/Auxiliary Lights Off	No	Yes	No	Yes
Engine Control Module DeviceControl Packet Analysis					
07 AE ... E5 EA	Initiate Crankshaft Re-learn; Disturb Timing	Yes	Yes	Yes	
07 AE ... CE 32	Temporary RPM Increase	No	Yes	Yes	Yes
07 AE ... 5E BD	Disable Cylinders,Power Steering/Brakes	Yes	Yes	Yes	
07 AE ... 95 DC	Kill Engnie, Cause Knocking on Restart	Yes	Yes	Yes	Yes
07 AE ... 8D C8	Grind Starter	No	Yes	Yes	
07 AE ... 00 00	Increase Idle RPM	No	Yes	Yes	Yes
Electronic Brake Control Module DeviceControl Packet Analysis					

07 AE ... 25 2B	Engages Font Left Brake	No	Yes	Yes	Yes
07 AE ... 20 88	Engages Font Right Brake/Unlocks Front Left	No	Yes	Yes	Yes
07 AE ... 86 07	Unevenly Engages Right Brakes	No	Yes	Yes	Yes
07 AE ... FF FF	Releases Brakes, Prevents Braking	No	Yes	Yes	Yes