Embedded software for new engine controller

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Titel Programvara för inbyggt realtidssystem för motorstyrning
Title Embedded software for new engine controller

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Sammanfattning
Abstract

This thesis describes software development for and testing of a new prototyping system for engine control units used at DaimlerChrysler. The system uses advanced new hardware to implement the engine controller. The purpose of the new hardware is to reduce the cost for the development of new engine control units without sacrificing performance. This is achieved by using hardware designed specifically for engine control. With the help of advanced software tools it should also be possible for people without detailed knowledge about the hardware or programming to work with the system during development.

The development of drivers for the hardware and a communication protocol to allow communication between the ECU and external units is presented. An application to allow engineers to perform measurements and calibrations during the development of the engine controller is also assembled and tested. It should be possible for people without knowledge about programming the system to use and alter this application.

The testing shows that the current system is functioning satisfactory, but it is also concluded that modifications might have to be made in the future when the engine controller is expanded to perform more functions. It is also concluded that some modifications to the software could be made to increase the performance of the system. It is believed that the described development system will be very powerful once it has matured.

Nyckelord
Keywords ECU, embedded system, vehicular system, rapid prototyping

ABSTRACT

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Linköping, November 2001
Johan Källström

ABBREVIATIONS

ADW	ARM Debugger for Windows
AIEC	Automotive Integrated Electronics Corporation
APIC	ARM Processor Interrupt Controller
ARM	Advanced RISC Machines
ASIC	Application Specific Integrated Circuit
AXD	ARM eXtended Debugger
CAN	Controller Area Network
ECU	Engine Control Unit
FPGA	Field Programmable Gate Array
GUI	Graphical User Interface
ICE	In-Circuit Emulator
IDE	Integrated Development Environment
ISR	Interrupt Servicing Routine
IRQ	Interrupt Request
KWP2000	Keyword Protocol 2000
LED	Light Emitting Diode
LLIB	Load/Logic Interface Board
PWM	Pulse Width Modulator
RISC	Reduced Instruction Set Computer
RTEC	Real-Time Engine Controller
SCI	Serial Communication Interface
SOC	System On Chip

CONTENTS

LIST OF FIGURES

1 Introduction

This thesis describes work carried out on DaimlerChrysler's new development system for engine control units, ECU:s. The work was carried out at DaimlerChrysler's research and development department in Esslingen, Germany. This chapter gives a short introduction to the problem that was to be solved and also gives a reader's guide to the thesis.

1.1 Background

DaimlerChrysler in Esslingen has recently started working on a new system for ECU development. The centre of the system is a real-time engine controller developed by AIEC, Automotive Integrated Electronics Corporation. This engine controller is implemented using a processor core provided by ARM, Advanced RISC Machines. For the development of control algorithms Matlab and Simulink are used, and with the help of Real-Time Workshop these algorithms can be transformed to embeddable C code. This way fast and efficient development of engine control functions can be performed. When development is finished, the engine controller will be fabricated as a System On Chip, SOC.

The first ECU:s started appearing in cars sometime in the mid 1970's. There were two main reasons for this. Firstly the high priced fuel had created a need to lower the fuel consumption. Secondly the allowed emission rates had been lowered, forcing car manufacturers to think of ways to reduce emissions from their engines. This could be done with the aid of an ECU, which enabled a more accurate control of engine functions than previously used mechanical methods. These mechanical methods had involved, among other things, step up converters for the car battery creating thousands of volts, mechanical "distributors" for choosing the right sparkplug and other crude methods. Scientists knew that this was bad for power and pollutants. To achieve better results it would be necessary to develop new technology to make it possible to more accurately mix fuel and air and ignite at the right moment. It was easily understood that this could not be achieved by using the mechanical devices, and interest soon turned to microprocessors.

The purpose of the ECU is to precisely mix air and fuel, and then ignite this mixture at exactly the right moment. It is also possible to monitor the engine and diagnose unexpected

and unwanted events. This information can then be used for service of the engine. For the ECU to be able to work properly it is necessary to use sensors, measuring data critical to the engine's function. Examples of data needed to be measured are crank- and camshaft rotational position, throttle position and rate of throttle position change. Before the input from the sensors in the engine can be processed, it must be converted to digital form. To perform the analogue to digital conversion the ECU is equipped with a number of A/D converters. Communication is done with Controller Area Network, CAN, communication busses, which provide fast and reliable communication in the tough automotive environment. For a presentation of the theory of automotive control systems the reader is referred to (Kiencke & Nielsen, 2000).

More advanced engine control functions soon demanded more powerful software for calculations, which in turn raised the demands on the microprocessors used for the ECU:s. For really sophisticated diagnostic functions it can be said that they need about the same CPU usage as the engine controller. One disadvantage with microprocessors provided by some manufacturers is that they are general-purpose in nature, and therefore might not be very well suited for everybody's specific needs. The reason for semiconductor manufacturers to produce general-purpose devices is that they can be used for many different applications, which means that the manufacturer can achieve a more cost efficient development and production.

For the customer on the other hand, the effect can be quite the opposite. The general-purpose microprocessors can not offer optimal performance for every specific task, and to compensate for this it might be necessary to consider investing in more advanced, and therefore more expensive, microprocessors. By using a peripheral that is specifically aimed towards engine control applications it is possible to achieve high performance at a lower cost. It might also be possible to implement functions that would be unthinkable when using a general-purpose device. This has been one of the main design goals when developing the DaimlerChrysler real-time engine controller, RTEC.

1.2 Objectives

The objectives of the work described in this thesis were to develop software that was needed for the engine control unit and the development system described above. This software could include drivers for the various engine control functions, I/O routines and routines needed for

the automatic code generation from the Matlab environment. At the department there is currently a development system using a power PC based ECU. With this system it is possible to use Simulink to design control structures and have C code for the ECU automatically generated. Graphical environments for measurements and calibrations of the ECU can also be generated from the Simulink environment. This means that people without knowledge about hardware and programming can work with the system. It is desired to develop the software for a similar system using the ARM hardware to implement the ECU.

Work came to focus on the implementation and testing of a communication protocol, keyword protocol 2000 (KWP2000), which is used at DaimlerChrysler for communication between an ECU and a diagnostic tool or another ECU, using RS232 serial communication.

Since the development system is brand new and has not previously been used at DaimlerChrysler in Esslingen, some of the work would also include setting up and testing the system and some of the functions of the engine controller.

1.3 Reader's guide

As a guide to the contents of this document, the following short summary of the chapters is given:

- Chapter 2 describes the various parts of the development system that was used during the work.
- Chapter 3 provides some information about things worth knowing when performing software development for the RTEC.
- Chapter 4 presents the ARM Processor Interrupt Controller, APIC, how it works and what initialisations have to be done for interrupt handling to function correctly. It also describes how the APIC was used for the implementation of interrupt driven serial communication on the system.
- Chapter 5 describes the Serial Communication Interface, SCI, that is implemented in the engine control system and some drivers developed for it to be used for the implementation of a communication protocol.
- Chapter 6 describes how the communication protocol KWP2000 is defined and how it was implemented and tested.

- Chapter 7 describes how the implementation of the protocol was slightly changed to work correctly with a software tool used for ECU measurements and calibrations, and also gives an example of how it was tested.
- Chapter 8 finally gives some conclusions and suggestions on how work could proceed in the future.

2 The development system

This chapter gives a short introduction to the various parts of the development system. The system consists of hardware provided by ARM and AIEC for the implementation of the engine controller, a power electronics board for connection to the engine and software tools for development of control functionality.

2.1 Overview of the development system

The development system and its various components are shown in figure 1 below.

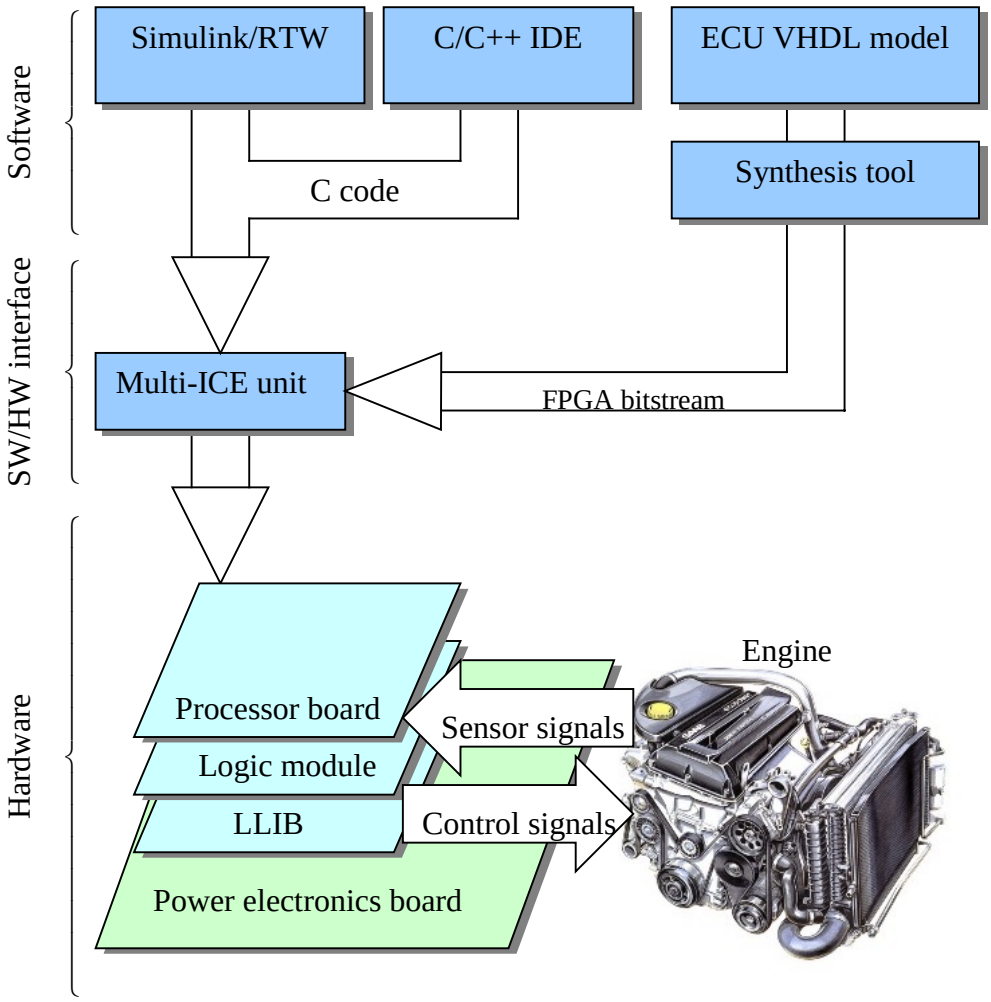


Figure 1: The development system and its components

The advanced hardware used in the system has been designed specifically for controlling DaimlerChrysler engines, which should make it possible to develop high performance ECU:s at a low cost. The processor board, the logic module and the LLIB are used to implement the ECU by programming them with a synthesised VHDL model. The ECU will later be implemented as a SOC. The software tools should make it possible to develop and test engine control functions as fast as possible, without knowing any details about how the ECU is programmed. This is accomplished by using Real-Time Workshop to automatically generate the code needed for the system. The code is downloaded to the system with the Multi-ICE unit. A description of each part of the development system is given in the following sections of this chapter. To fully understand what is presented it might be useful for the reader to have a basic knowledge about digital electronics and computer architecture. For a description of application specific integrated circuits (ASIC), field programmable gate arrays (FPGA) and digital electronics in general the reader is referred to (Schilling & Belove, 1989). In (Roos, 1995) a presentation of computer architecture, like for instance reduced instruction set computers (RISC) can be found.

Since both software and hardware are quite sophisticated, a lot of time had to be spent getting familiar with the equipment before work could really begin.

2.2 Real-time Workshop

Real-Time Workshop (RTW) is a software tool that is to be used together with Matlab and Simulink. Simulink provides an environment where control algorithms can be implemented and simulated in a fast and simple way. By using some of the available toolboxes for Matlab development can be performed even faster. When a control function has been implemented and tested in Simulink it is possible to use Real-Time Workshop to transfer the Simulink model to ANSI C code, thereby making it possible to, for example, download it to a microprocessor system as shown in the figure above.

A rapid prototyping system like this shortens the time needed for development. Since not as much time has to be spent on writing code by hand, the engineer can concentrate on developing and refining the important control algorithms. It is usually necessary to make changes to the algorithms several times during development, and then perform testing to see if the desired performance can be reached. For this kind of iterative design procedure a development system using Real-Time Workshop can be ideal.

The code that is generated can be affected by choosing between a number of different target templates, depending on what your needs are. If none of the available standard templates are considered suitable the user has the option to design a custom template. This way it is possible to have code generated that will give as high performance as possible when running on the system in question.

2.3 ARM Developer Suite

ARM is a semiconductor manufacturer offering microprocessors and a number of development tools. Among other things they were the ones who developed the world's first commercial RISC processor (in 1985). The ARM developer suite, ADS, is a software package that has been designed for developing applications for ARM based systems. The ADS has the following features:

- Code generation tools with embedded C++ and C compilers, assembler and linker
- Code Warrior Integrated Development Environment (IDE) for Windows or UNIX
- Enhanced GUI debuggers (AXD and ADW)
- Instruction set simulators
- Support for new ARM cores
- On-line documentation
- ARM applications library
- RealMonitor, which is a powerful software tool that can be used for debugging real-time systems, which can sometimes be somewhat complicated

The ADS comes with two debuggers: ARM eXtended Debugger, AXD, and ARM Debugger for Windows, ADW. For the work described in this report AXD was used. This is a tool that can be used to monitor and control a program that is being executed on an ARM system. It is also used for download of program code to the system. The debugger has various functions that can be useful when testing the developed software. The programmer has access to memory, registers and program variables. This can be useful for debugging, for instance to check that each register contains the right value during program execution. Breakpoints can be set to halt execution at points that are considered critical.

Figure 2 below shows the debugger GUI, and some of the available functions. To the left of the picture there is a window showing the variables of the program currently running. The two windows in the middle show the program C code and disassembly. Breakpoints are added simply by double clicking a point in one of these two windows. The window in the bottom right corner of the picture shows the memory contents of the system. This can be useful for finding hardware functions that are not operating correctly, causing some memory locations to contain the wrong values. To the left of the memory window is the command line interface. This can, for instance, be used to write values to memory. During the work described in this report the ARM electronics were used for development without a motherboard. For this kind of development system a memory write (smem 0x1000000C 0x04, as seen in the figure) has to be done before a program can be executed on the system. Otherwise the electronic boards will still think that they are connected to a motherboard, and will therefore try to fetch program code from the wrong memory location. This memory write can be performed manually from the debugger or be put in a script that is executed automatically when the debugger is started.

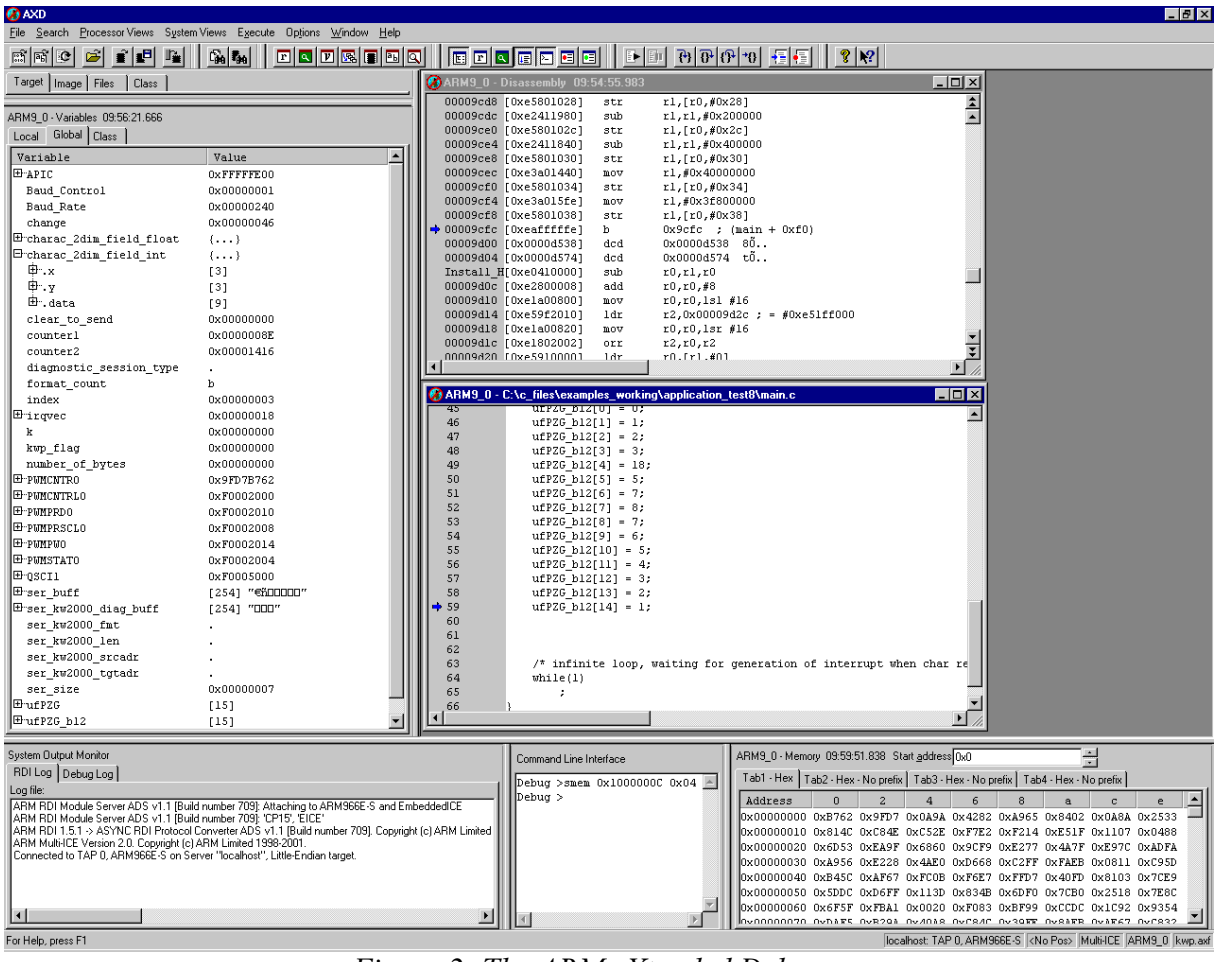


Figure 2: The ARM eXtended Debugger

With the ADS there is also a code development environment included, a special ARM version of the CodeWarrior IDE from Metrowerks. This tool together with the compilers is used to create code that is particularly suited to run on an ARM based system such as the one used for this work. It comes with library functions that have been provided by ARM, as to make code development as fast and efficient as possible. Creating applications is very simple, you just add your code files to a project and compile. The IDE is connected to the debugger, so that a program can be compiled, downloaded to the system and run right from the IDE.

To be able to download the program to the system and debug it a third software is needed, the Multi-ICE server. This provides a connection between the debugger and the Multi-ICE box, which will be described in the next section of this chapter. From the Multi-ICE server interface a configuration file is loaded, or the server can be configured automatically. It is then left running during the debugging of the program. It is also possible to reset the target from the server interface.

It took some time to get used to all the functions of the software used. But once you get familiar with the programs they are very easy to use and work really well. No real problems or shortcomings of the software were discovered during work.

2.4 Multi-ICE

Multi-ICE is a JTAG-based In-Circuit Emulator (ICE). This unit, together with the Multi-ICE server, is what makes debugging of the system possible. It is possible to perform debugging of the embedded processor at maximum clock frequency, and on-chip debugging of multiple ARM and mixed architecture devices is also possible. In addition to that you can also debug slow or variable frequency designs and low voltage cores (down to one volt). The device supports all the current ARM cores and has fast download and stepping speeds. The Multi-ICE unit can be seen in figure 6, used for programming the FPGA:s on the circuit boards.

2.5 The ARM processor board

ARM provides development platforms enabling flexible development of a number of different systems. The ARM processor board can be used for developing as a standalone system, together with an ARM Integrator motherboard or integrated into an ASIC prototyping system. It is also possible to connect a number of boards (up to four) on top of each other to further expand the system.

The board comes equipped with the following features:

- ARM966E-S microprocessor core
- Volatile memory comprising up to 256MB of SDRAM (optional) plugged into the DIMM socket and 1MB SSRAM
- Core module FPGA which implements SDRAM controller, system bus bridge, reset controller, interrupt controller, status- , configuration- and interrupt registers
- SSRAM controller PLD
- Clock generator
- Integrator system bus connectors
- Multi-ICE debug connector
- Logic analyser connectors for local memory bus
- Trace port

Figure 3 below shows how the ARM processor board looks and what different components are on it (as described in the text above).

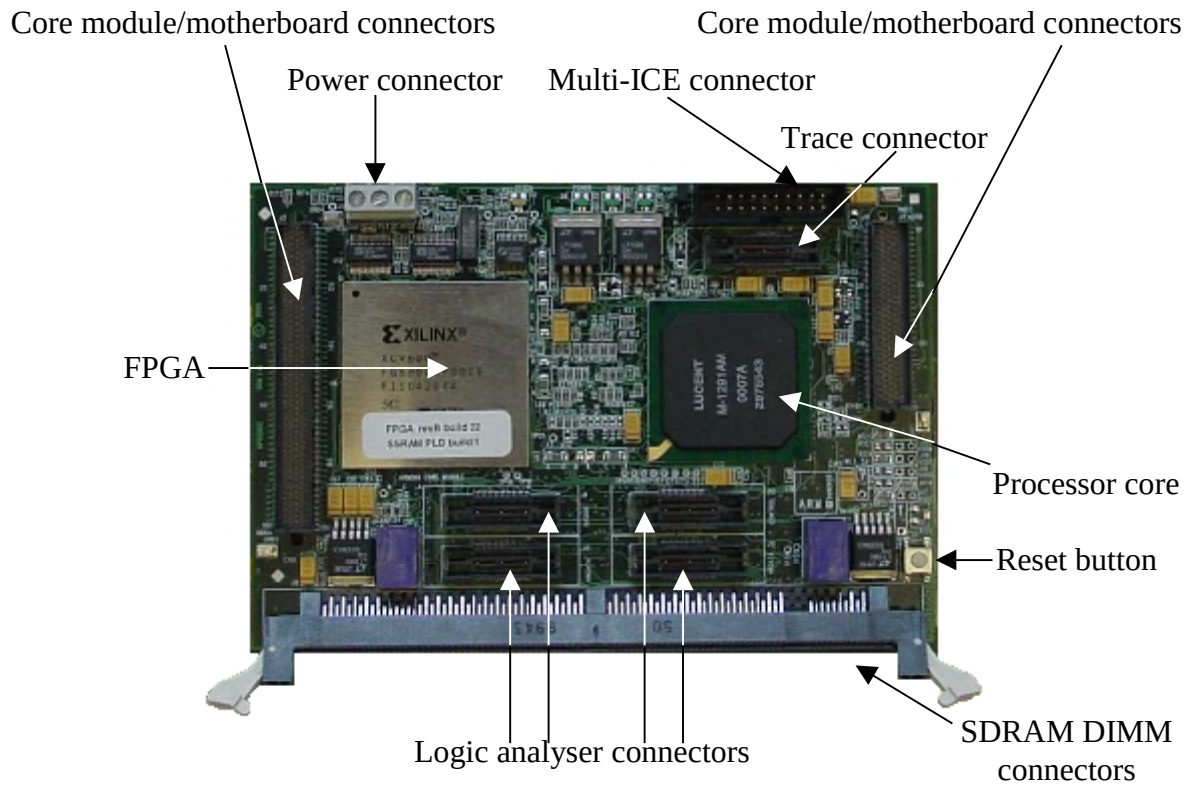


Figure 3: The ARM processor board

The core module/motherboard connectors, as shown in the figure, are used to stack a number of boards or to connect the processor board to an ARM motherboard. For our system the ARM processor board is used for development together with an ARM Integrator logic module and a Load/Logic Interface Board, LLIB, which are described in the following two sections of the report.

This is a very flexible development system, which allows for fast prototyping to be performed. It is easy to implement and test new functions for applications. The real-time engine controller used for our system has been specifically designed for use together with an ARM core. This means that it has been possible to implement it in such a way that maximum performance is reached. This is not always possible when building a control system using a general-purpose microprocessor. When development is finished the ARM core and the RTEC will be fabricated as a SOC.

2.6 The Integrator logic module

The Integrator/LM logic module is a device designed by ARM to be used as a platform when developing systems using their ARM cores. The logic module can be used in four different ways:

- As a standalone system.
- With an ARM processor board and Integrator motherboard.
- As a processor board with the Integrator motherboard if a synthesised core is programmed into the FPGA on the board.
- Stacked without a motherboard with one module in the stack providing the same system controller functions as a motherboard would.

Our system uses the last option, a stack with an ARM processor board, an Integrator logic module and the LLIB. The implementation of the RTEC is located in the FPGA on the Integrator logic module. It is possible to make modifications to the RTEC, for instance if an error in the old implementation is discovered, and download this new implementation to the FPGA. This is of course very practical when testing a new system.

Figure 4 below shows the architecture of the Integrator logic module, and what is available to the developer. The board has basically the same connectors as the ARM processor board, to allow connecting it to the Multi-ICE unit and logic analysis tools. It also has connectors to make it possible to add the board to a board stack. For prototyping there is also a grid of connections to the FPGA that is located on the board. This prototyping grid can be used to access the inputs and outputs of the FPGA. It could for instance be used to:

- Wire to off-board circuitry.
- Mount connectors.
- Mount small components.

This possibility can be very useful when developing new systems, where for example connections to off-board equipment of various kinds are necessary.

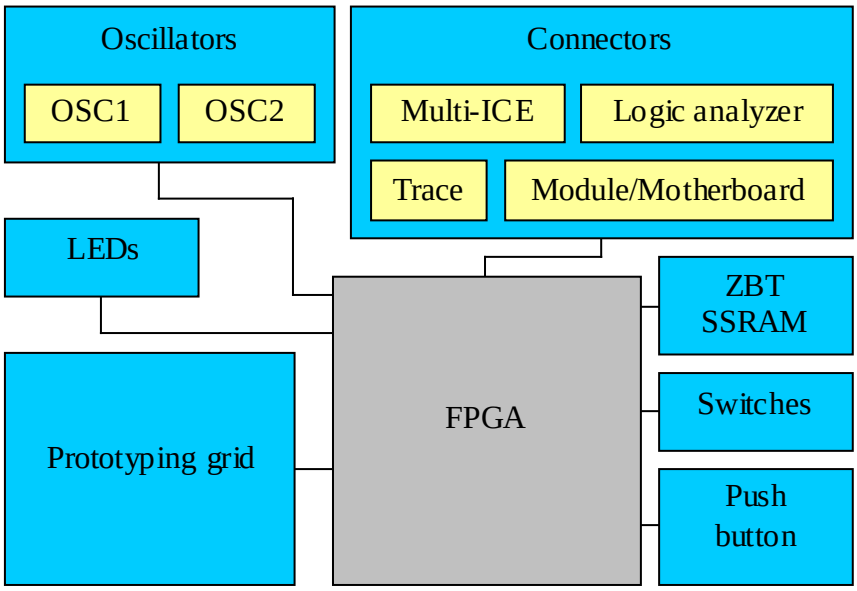


Figure 4: The architecture of the Integrator logic module

The logic module FPGA can be programmed to perform different functions. With the help of VHDL or Verilog a description of the logic in the FPGA for a certain functionality is created. By using logic synthesis this description is turned into an Electronic Data Interchange Format, EDIF, netlist that is technology specific (for instance to be used with Xilinx FPGA:s). Apart from a VHDL/Verilog description you also have to provide the synthesis tool with information about the technology you are using. The EDIF netlist is then combined with some requirements on the design to produce a final output for the FPGA:s to be programmed with.

Different software have different requirements and options, but the information you supply the program with to perform the whole procedure usually contains the following:

- A list of HDL files.
- The target technology.
- Required optimisation.
- Timing and frequency requirements.
- Required pull-ups or pull-downs on the FPGA input/output pads.
- Output drive strengths.

For our system Xilinx hardware is used, and by using Xilinx specific software and the EDIF netlist a bitstream file is generated. This file is then used for programming the FPGA:s. Figure 5 below shows the program flow when producing a new bitstream for the FPGA:s to be programmed with.

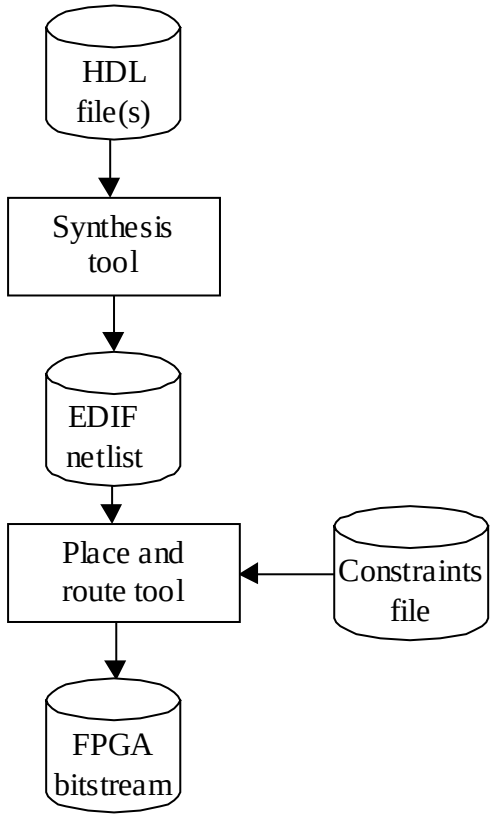


Figure 5: Producing a bitstream for the FPGA

This programming procedure might have to be repeated several times before a fully functioning and stable system has been achieved. The method is very efficient and allows for

fast development of new systems. The actual downloading to the FPGA:s is done with the help of Multi-ICE by connecting it to the logic module as shown in figure 6 below.

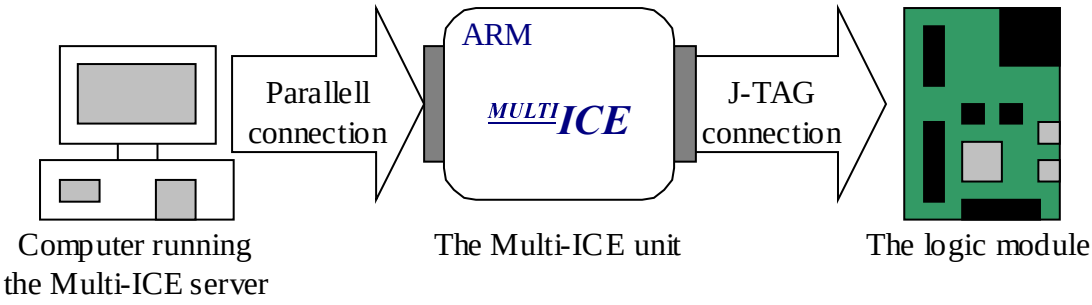


Figure 6: Downloading a bitstream to the FPGA

2.7 Load/Logic Interface Board

The load/logic interface board, LLIB, is an interface board designed for prototyping SOC integrated circuits. The primary function of the device is to provide an interface between a load board with power electronics and a logic board with microprocessor and peripherals. The 3.3 volts used on the logic board are converted to 5 volts for the load board, and the other way around. The LLIB is also equipped with A/D converters to handle the conversion of analogue sensor signals from the load board to digital signals that can be handled by the logic board. There are also two discrete CAN interface circuits for communication purposes. A maximum of 152 signals can be transferred between the load and logic boards. This is controlled by programming the FPGA:s on the LLIB. The pins on the board can be programmed as inputs, outputs or bi-directional pins. The programming is done in the same way as for the integrator logic module. A block schedule of the interface between load board and logic board is shown in figure 7 below.

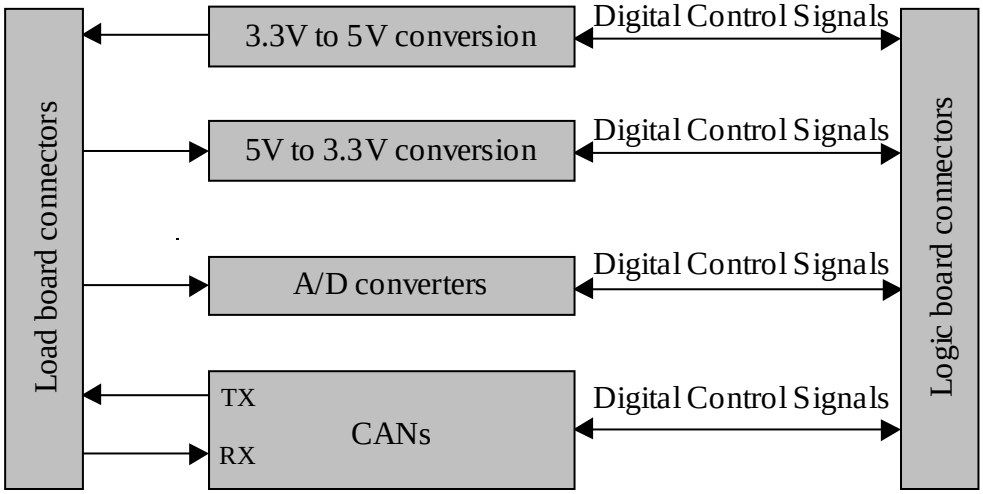


Figure 7: Block schedule of the LLIB

2.8 The engine controller

The real-time engine controller has been developed by AIEC and it is available as a VHDL model. By using the procedure described above the FPGA on the logic module can be programmed with this model.

The RTEC is a peripheral that has been developed for use together with a microprocessor core for controlling internal combustion engines. It was designed to increase the performance of the engine and decrease the exhaust of pollutants by making a precise delivery of ignition and injection pulses possible. By using an advanced design the interrupt handling performed by the controlling processor has been reduced, giving a great increase in throughput. This in turn makes it possible to use more complex control algorithms, since the processor can spend more time on processing these.

Because of the intelligent hardware it is not necessary to write that many low level routines for the drivers, which makes software development simpler, faster and cheaper. The fact that the RTEC is not a general-purpose device but instead dedicated hardware gives high performance at lower cost for the engine controller.

2.9 Comments on the development system

Both the software and the hardware used during the work on this thesis are quite advanced and complex. It was therefore necessary to do a lot of literature studies before the actual software development could begin. Of course it also took some time to get used to the various development programs and to learn to take advantage of their available features as much as possible.

The hardware developed exclusively for DaimlerChrysler is very new and has not yet been used that much. That meant that some problems appeared during work with the hardware not acting exactly as you expected it to. This was usually due to the FPGA:s being programmed with incorrect configuration files, and the solution was simply to have new configuration files generated and downloaded to the circuit boards. Though not a very complicated procedure, it was still somewhat time-consuming.

3 Programming the engine controller

This chapter gives some information about what is worth considering when performing software development for a real-time embedded system such as the RTEC. During such software development it is necessary to take considerations not necessary when developing for a computer platform like a PC environment. A real-time system is a system that must react on certain events and deliver an appropriate response on time, while an embedded system is a computer system that interacts with its environment. Some general information and some information specific for the development performed on our system are given. A description of software and hardware for embedded systems can be found in (Gupta, 1995). For a presentation of real-time systems the reader is referred to (Burns & Wellings, 1997).

3.1 Software development for a bare-board environment

When programming for a bare-board environment, that is a system where the processor is working without the aid of an operating system, the programmer must have more knowledge about how the system in question works. Some of the things that must be dealt with are the I/O structure, interrupt structure and register set of the system. You also have to consider how much program and data memory there is available on your system.

Access to external units like serial ports, A/D and D/A converters is performed by reading and writing the control and data registers of these units. The programmer himself must make sure that all the units are initialised in the right way before they are used. The functions available in standard I/O library files like stdio.h and others can no longer be used, since standard I/O does not work for an embedded application. Instead the programmer must write his own version of the functions in these files that are needed for the system. The software tools that come with ADS do however give the programmer the possibility to write messages to a console window in the debugger, which can be useful for debugging.

When transferring old, non-embedded code, to an embedded application you might have to consider what has been mentioned above. It is very possible that some changes have to be

made for the code to be able to run on the embedded application, especially if it uses many standard C library functions.

A short discussion on software development for bare-board environments and a good example can be found in (Bilting & Skansholm, 2000).

3.2 C/C++ versus assembly language

There are a number of factors that should be considered when choosing between doing programming in assembly or in a high level language like C or C++. Some factors are throughput, memory requirements, development schedules, portability and how experienced the programmer is. For a real-time application it is often essential that the services are performed as fast as possible.

A program written in assembly language will always be more efficient than a program written in C, but the development time for the assembly code will most likely be longer than that for the C code. When you start working with a new development system you might also have to spend time learning the assembly instructions for that particular system, while most programmers already have a good knowledge of C language. This means that if it is important to get development started a soon as possible it might be better to use C as your programming language, provided of course that it is possible to fulfil the requirements on the program when coding in C.

A program written in C can also later on be ported to other systems, perhaps with some slight modifications. A program written in assembly on the other hand can not be ported, but must instead be completely rewritten. If modifications have to be made to the program in the future by someone else than the original author it is also much easier to read and understand a program written in a high level language.

When you try to optimise a program you will usually find that there are a few sections of the code that take significantly more time to execute than others. Some say that a program spends 90% of the time in 10% of the code. One way to deal with optimisation could then be to write these parts of the program in assembly, thus increasing system performance while not having to spend too much time doing assembly coding.

3.3 Software development for the real-time engine controller

The real-time engine controller that is used in the system is a sophisticated device developed by AIEC. One of the objectives during the development of this device has been to put as much functionality as possible in the hardware. The purpose of this is to obtain a system where the developer has to spend as little time as possible writing drivers for the functions of the engine controller, giving him more time to focus on developing control functions.

One of the goals has also been to make it possible to do all the driver development in a high level language like C or C++. On some other systems it is often necessary to write drivers in assembly to get high enough performance. By using intelligent hardware AIEC has made this unnecessary when writing drivers for the RTEC. This means that the development can be performed faster.

Figure 8 below is a block schedule of the RTEC that shows the various parts of the device, as presented in (DCRTEC Reference Manual 0.2, 2001).

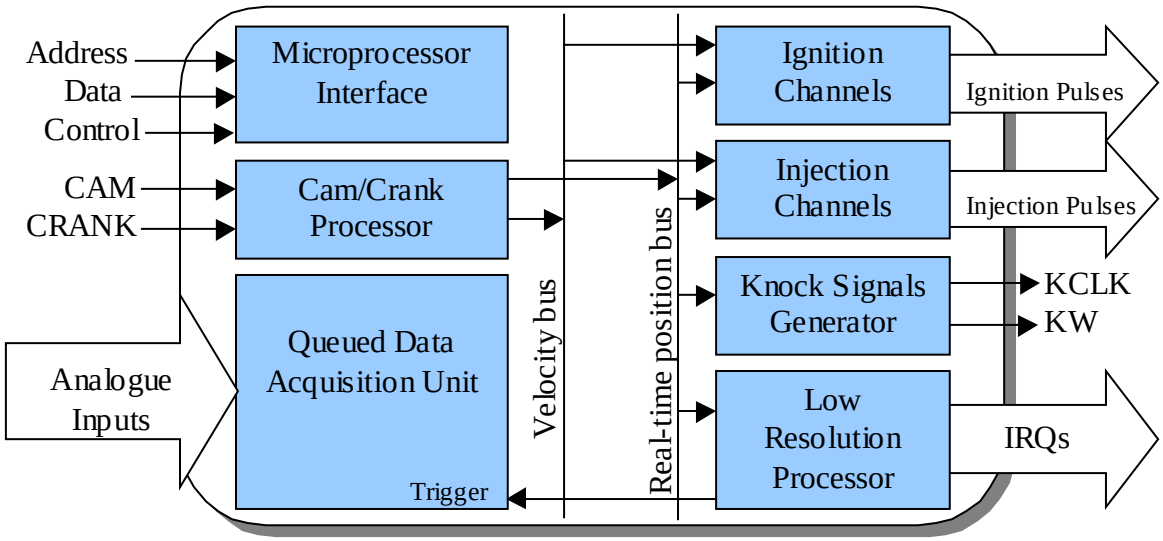


Figure 8: Block schedule of the real-time engine controller

The parts that the RTEC consists of are described below.

- The microprocessor Interface is responsible for monitoring the microprocessor control and address lines and generating correct read and write signals to the RTEC registers.

- The cam/crank processor keeps control of the cam and crank positions. It has got a resolution of 0.1° after synchronisation. The synchronisation is done with the help of so called teeth patterns.
- The queued data acquisition unit handles the A/D conversions. There are 32 analogue inputs that are connected to a multiplexer. The conversion is performed using successive approximation with 10-bit resolution, and can be position- or time-based-triggered or initiated by software. After the initialisation of the queued data acquisition the conversions are performed automatically, independently of the microprocessor.
- The ignition channels handle the task of asserting the ignition pins. They are programmed by writing to two registers: the dwell time register and the ignition advance register. The dwell time register decides when the pins are asserted and the ignition advance register decides when the pins are de-asserted. The RTEC supports most of the ignition strategies commonly used. After the two register writes have been performed, everything works without disturbing the microprocessor.
- The knock signal generation is used for analysing knock intensity.
- The injector channels are used for implementing the chosen injection strategy. Most commonly used strategies, like simultaneous injection, group injection and sequential injection, are supported. After the initialisation the programming is done by register writes. You can choose between angle/time mode (where an injector output pin is asserted for a specified time starting at a programmed angle) or time/angle mode (where the output pin is asserted at a programmed pulse time before the specified end angle).
- The low resolution processor has a resolution of 1.0° compared to the cam/crank processor's 0.1°. It can be used for starting A/D conversions at specified angles, generating microprocessor interrupts at programmable engine positions and several other functions. After the initialisation the low resolution processor works independently of the microprocessor.

In addition to this engine control functionality there are also serial communication interfaces, pulse width modulators, general purpose I/O and similar available for development.

Access to the different parts of the engine controller, as shown in the figure above, is performed with memory-mapped registers. Driver development for the RTEC basically means that you write to a number of different control registers to set the appropriate bits for a certain function. By reading various status registers the software can control what is happening in the

system, and thereafter take necessary actions. It is also possible to have interrupts generated when flags are set. This can for instance be used to make sure that the system always handles the most urgent task.

When declaring variables that should be used as flags or similar, it must be determined if these variables can be changed by external devices, for instance in an interrupt routine. If that is the case they should be declared with the keyword **volatile**, like this (ready is a variable that is changed when a flag in one of the status registers of the RTEC functions, for instance the serial communication interface, is set):

```
extern volatile int ready;
```

Otherwise the compiler might perform optimisations that will cause the program to operate in the wrong way. The following while-loop, for instance, would not work if the variable ready had not been declared as **volatile**:

```
while (!ready)
{
        ….
}
```

If ready was not declared as **volatile**, the program might only read the value of the variable before the first turn of the loop, and then get stuck there forever. This sort of behaviour is prevented by the use of the **volatile** keyword.

Since the registers of the RTEC are changed by external devices when various events occur, the register variables should always be declared as **volatile**.

3.4 Setting up and testing the development system

After the hardware and the software described in chapter two had been installed, some software development was performed to make sure that the system was operating properly. A second purpose of this was to get familiar with the tools that were to be used later on.

The tools used are quite easy to get to know, and it does not take that long to get started with the development. The programs have many useful features that proved very helpful for debugging of programs that were not operating correctly.

Some simple programs were developed to test access to various registers of the system, for instance general purpose I/O, LED:s and numeric displays. After this learning period, the development of functions for the real engine control system was started, which is described in detail in the following chapters.

4 The ARM Processor Interrupt Controller

This chapter describes the ARM processor Interrupt Controller, APIC, and some routines that were developed for it. Those routines were later to be used for implementing interrupt driven serial communication on the system. Some information is also given about how the system had to be initialised in order for the interrupt handling to work correctly. For a description of how interrupt handling in computer systems works the reader is referred to (Roos, 1995).

4.1 Information about the APIC

The ARM processor itself does only provide two interrupt sources. For an engine control system this is quite insufficient, since a lot of interrupts need to be generated by the different sensors in the engine and handled simultaneously by the control system. To solve this problem AIEC has developed the ARM Processor Interrupt Controller, which adds an additional number of thirty interrupt sources to the system, thereby making it more capable of handling the demands of engine control. These interrupt sources can be assigned to different inputs on the development boards by reprogramming the FPGA:s. Among the sources currently available are the SCI, the RTEC low resolution processor and the RTEC queued data acquisition. The structure of the APIC is shown in the block schedule in figure 9 below. Details about the APIC are presented in (APIC Reference Manual 0.2, 2001).

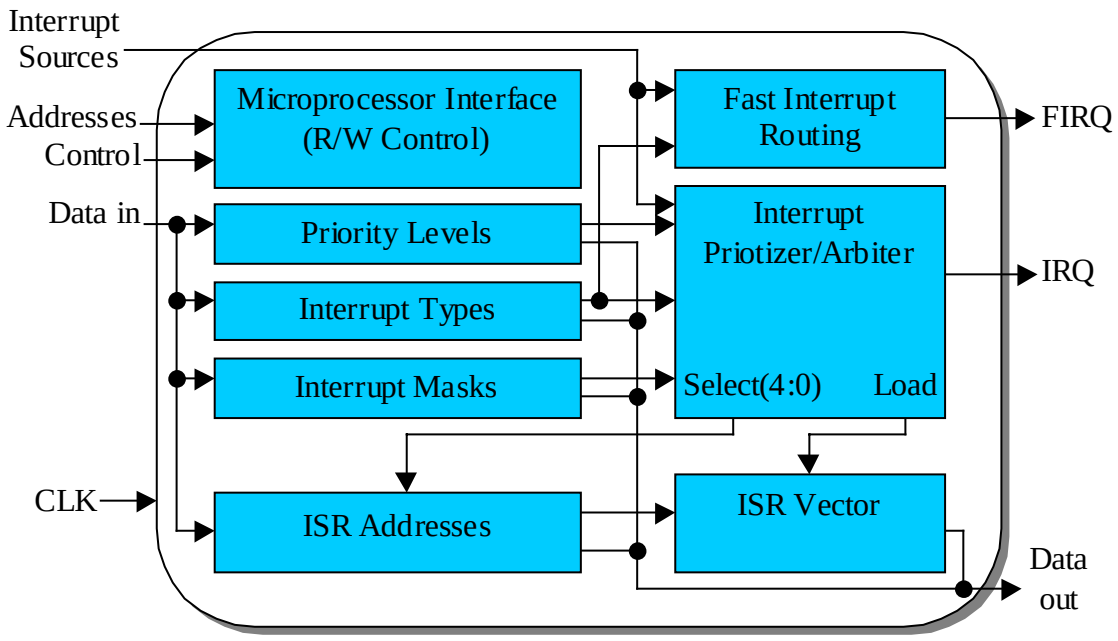


Figure 9: Block schedule of the APIC

For each interrupt source the programmer decides on what priority the source should have, sets the address of the associated interrupt servicing routine, ISR, and decides if the source should be used as a hardware or software interrupt source. A hardware interrupt is generated when a flag in a status register of one of the RTEC functions is set, while a software interrupt can be generated at any time by the program code by doing a write to the control register of the software interrupt source. It is also possible to define an interrupt source as a fast interrupt, FIRQ. When many interrupt sources are used in the system, some thought must be put into assigning each source the right priority.

When an interrupt is generated the ISR address of the source is moved into the ISR vector register of the APIC, while the program counter jumps to address 0x18. Located at address 0x18 is a branch to the address located in the ISR vector register. When the ISR vector register is read by the processor the interrupt is cleared, so that the program will not immediately jump back into the servicing routine after the interrupt has been handled.

It is very important, especially for a system with a lot of interrupts generated, that the interrupt handling is done in an effective way. Effective interrupt handling means higher throughput and gives the processor more time to work with the important engine control functions. That way the system performance is increased. This is something that has been one of the major objectives during the design of the APIC.

Figure 10 below shows the available registers and their contents, as presented in (ENCORE Reference Manual 0.3, 2001).

Register Name	Access Type	Hex Address	Bit Position															
			31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
			15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
APICCNTRL	R/W	FFFFFE00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	FENA	IENA
APICISTAT	R/W	FFFFFE04	IRQ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	PRI				
APICFCNTRL	R/W	FFFFFE08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	FIRQS				
APICISRVEC	R/W	FFFFFE0C	ISR Address of Current IRQ Interrupt Source															
APICFISRVEC	R/W	FFFFFE10	ISR Address of FIRQ Interrupt Source															
APICEOI	WO	FFFFFC14	End of Interrupt															
APICISRVA0	R/W	FFFFFE20	ISR Address For Interrupt Source 0															
APICISRVA31	R/W	FFFFFE9C	ISR Address For Interrupt Source 31															
APICCNTRL0	R/W	FFFFFEA0	ENA	SWT	ACTLV	ED/LV	SW/HW	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	PRI				
								•										
APICCNTRL31	R/W	FFFFFF1C	ENA	SWT	ACTLV	ED/LV	SW/HW	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	PRI				

Figure 10: The APIC registers

Following below is a short description of each register, as presented in the (APIC Reference Manual 0.2, 2001).

- APICCNTRL: This register contains the control bits for enabling the generation of interrupts.
- APICISTAT: This status register shows what interrupt source is currently being handled and the priority of this source.
- APICFCNTRL: This is a status and control register for the fast interrupt request, FIRQ.
- APICISRVEC: This register is loaded with the address of the interrupt servicing routine of the interrupt source currently being handled.
- APICFISRVEC: This register contains the address of the interrupt servicing routine of the fast interrupt source.
- APICEOI: This register should be written to at the end of the interrupt servicing routine to signal to the APIC that the interrupt handling has finished.
- APICISRVA0 -> APICISRVA31: These registers contain the addresses of the interrupt servicing routines of the available interrupt sources.
- APICISCTL0 -> APICISCTL31: These are the control registers for the available interrupt sources.

4.2 Initialisation of the system

In order for the interrupt handling to work properly it is necessary to make sure that no information is lost when an interrupt is generated, and thereby guarantee that the program can continue to execute when the interrupt has been serviced.

In (ARM Developer Suite Version 1.1 Developer Guide, 2000) two different ways to handle interrupts are presented. The simplest way to do it is by using the **_irq** keyword in front of the declarations of the interrupt servicing routines, like this:

irq_ void interrupt_servicing_routine(**void**);

By doing this you will let the compiler know that this routine is for handling interrupts and make it add code necessary for storing and restoring crucial registers before and after the routine, so that the interrupts work properly. In addition to that, initialisations of the stack space, stack pointers and other system functions needed for the interrupt handling will be

carried out. The problem with the **_irq** keyword is that it does not work for re-entrant interrupts, that is, no interrupt must occur during the servicing of another interrupt. If this would happen registers would be corrupted and the system would not work. This makes the **_irq** keyword useless for our system, since an engine control system with many interrupt sources definitely should be able to handle re-entrant interrupts.

When the **_irq** keyword is not used the programmer must use the second, slightly more complicated method, which involves making sure that the system is set up in such a way that everything will work once an interrupt occurs. This means that some initialisation code has to be written and executed at the start of a program.

When writing programs for the ARM system it is possible to choose from a number of different configuration options. Depending on what your needs are you might have to write more or less complex code to initialise the system in the proper way. The initialisation routines used for our system handle the initialisation of some system functions needed for the interrupt handling. Basically this involves setting up the stack space and initialising the stack pointers, which are used when an interrupt servicing routine is called. You must also initialise some flags used by the system, and finally it is necessary to make sure that the memory location 0x18 contains a branch to the address pointed to by the ISR vector register. Most of the initialisations can not be made from C language, but must instead be written in assembly.

When more interrupt sources are added to the system, or when other changes are made, it might be necessary to add more code to the initialisation routine, for instance to set up the stack space for the handling of fast interrupt requests, FIRQ. It might also be important to think about how the layout of the memory map will affect the performance of your system. No matter what your system is there will have to be ROM containing executable code at the address 0x0 after a reset. After that you could simply leave the ROM where it is, but to achieve maximum performance it can be necessary to perform a remapping of the memory. Our system, and engine control systems in general, rely on interrupts generated by sensor signals from various vital parts of the engine. The current system has 18 different sources for generation of hardware interrupts, and there are an additional 14 sources that can be used for generating software interrupts or for adding more hardware interrupt sources in the future. When more interrupt sources are used in the future it might be worth considering using one of the ROM/RAM memory remaps that are described in (ARM Developer Suite Version 1.1

Developer Guide, 2000) to speed up the interrupt handling. The code for this could then be included in the initialisation function for the system.

The above described initialisations are what is needed for the handling of a single interrupt on the system. To accomplish re-entrant interrupt handling the interrupt handler routine, IRQ_handler, must contain assembly code that stores all the relevant registers before executing the code tied to a particular interrupt, and then restores the same registers after the handling of the interrupt is finished. The interrupt servicing routine, rtec_int_isr, which contains the code to perform the tasks needed for the interrupt currently being handled can be written in C language and branched to from within the assembly code. At the end of the interrupt servicing routine any flags that caused the interrupt should be cleared and by writing to the APIC End Of Interrupt (APICEOI) register the program should signal to the APIC that the handling of the interrupt has finished, which means that a new interrupt can be handled. Each interrupt source should have an interrupt servicing routine like this.

Before the interrupt sources of the system can be used, an assembly-macro has to be called to enable the interrupt handling, by reading the cpsr flags and updating bit 7. There is a similar macro that does the opposite, that is it disables the interrupt handling. This macro could be used before a crucial segment of code that must not be interrupted by any of the interrupt sources.

4.3 Testing the APIC functionality

To make sure that the interrupt handling was working the way that it was supposed to, and to test some interrupt servicing routines that had been written, some simple test programs were created.

The following routines for the initialisation and handling of the interrupt sources were written for the system:

- system_init: a function that does the necessary initialisations of the system for the interrupt handling to work properly, as described above.
- init_interrupts_sci: a function used to initialise the interrupts needed for the serial communication routines developed further on.
- enable_interrupts: function to enable the generation of interrupts.

- interrupt_status: function to check the current status of the interrupt handling.
- enable_interrupt_source: function used to enable and configure one of the interrupt sources.
- generate_software_interrupt: function used to generate a software interrupt on one of the interrupt sources.

For testing purposes the interrupt servicing routines for the available sources were made to simply reset the source that had caused the interrupt and print a message to the screen. This was used to determine that the interrupt handling and the interrupt sources were working like they should.

During the testing of the APIC it was discovered that the interrupts were not cleared when the APICISR was read. This meant that this had to be done manually to prevent the program from immediately jumping back into the interrupt routine as soon as finished interrupt handling was signalled by writing to the APICEOI register, thereby causing the program to stall. By generating new configuration files for the FPGA:s this problem was later removed and the APIC was from there on functioning the way it should.

For the development described in this report the interrupts were used for interrupt driven serial communication, which was then used for the implementation of a communication protocol. The APIC was used for generating hardware interrupts when a character was received on the serial port. The interrupt servicing routine put the received characters in a buffer and called various functions depending on what commands had been received. Another interrupt source was used for generating software interrupts when a response to the received commands was to be sent. For timing of the messages sent, an interrupt driven timer was also implemented later on. This will be described further in the following chapters of the thesis.

4.4 Comments on the APIC and the developed routines

One of the advantages of the RTEC is that it has a lot of functionality built into the hardware that would usually have to be handled by writing code. This means for instance that not much low level code has to be written when developing drivers for the various functions of the system. For interrupt handling though, some low level code is needed before the system functions the way it should. This code is actually needed for the ARM hardware, and not for

the RTEC itself. But since this code does not have to be changed that often, it does not cause the developer that many problems.

For the work described here only a couple of the available interrupt sources were used. Adding support for the rest of the RTEC interrupt sources simply involves writing the interrupt servicing routine, rtec_int_isr, for each added source. This routine can be written in C language. The assembly IRQ_handler code will look the same for each interrupt source and can therefor be reused.

When more interrupt sources are added the developer will have to put more thought into assigning each source the right priority. For this thesis only four interrupt sources were used, which meant that it was not that difficult to decide which source should have the highest priority.

5 The Serial Communication Interface

This chapter describes the RTEC Serial Communication Interface, SCI, and the development of routines for the same. The previously developed APIC routines were used to implement interrupt driven serial communication on the system. This was later to be used for the implementation of a communication protocol that is used by DaimlerChrysler ECU:s. Some information about how serial communication and communication with external units work can be found in (Roos, 1995).

5.1 Information about the SCI

On the LLIB there is a 30-pin port for which different functions of the RTEC can be assigned. For our system two of the pins of this port were assigned to one of the two SCI:s that are implemented in the RTEC. These pins were to be used for serial communication with external equipment, like for instance a normal PC serial port. Routines for the SCI were developed for a couple of different purposes. Most of the routines were designed so that they could later be used for the implementation of the Keyword Protocol 2000, a communication protocol used by ECU:s with diagnostic capability. This implementation is described in chapter 6 of this report.

The SCI is implemented using the Motorola standard serial interface format. It can be used in byte mode or in buffered mode, where there is a 16 byte receive buffer and a 32 byte transmit buffer. There are control registers for choosing Baud rate, word length and parity type as well as enabling generation of various kinds of interrupts. There are also a couple of status registers available to the user.

The SCI is described in detail in (QSCI Reference Manual, 2001).

5.2 Developing routines for the SCI

Writing drivers for the SCI basically consists of accessing the proper register and setting control bits in such a manner that the desired function is achieved. After the control bits have been set the status registers are used to monitor the communication. The registers available

for the SCI in our system and the bits of these registers are shown in figure 11, taken from (ENCORE Reference Manual 0.3, 2001).

Register Name	Access Type	Hex Address	Bit Position															
			15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
SCI1DR	R/W	F0005000	Transmit / Receive Data															
SCI1SR	R/W†	F0005004	0	0	0	0	0	0	0	TDRE	TC	RDRF	RAF	IDLE	OR	NF	FE	PF
SCI1CR	R/W	F0005008	0	LOOP	WOMS	ILT	PT	PE	MODE	WAKE	TIE	TCIE	RIE	ILIE	TE	RE	RWU	SBK
SCI1BRR	R/W	F000500C	0	0	0	Baud Rate Divisor (System Clock/32)												
QSCI1CR	R/W	F0005010	ENQ	0	RBRKIE	RQNFIE	Receive Queue Near Full Count					TQOFIE	TQNEIE	Transmit Queue Near Empty Count				
QSCI1IBD	R/W	F0005014	0	0	0	0	0	0	0	0	Transmit Inter Byte Delay (System Clock/1024)							
QSC11SR	R/W†	F0005018	RXP	TXP	RBRK†	RQNF†	RQP	TQOF†	TQNE†	0	Transmit Queue Bytes Left to Transmit							
QSCI1RQP	R/W	F000501C	0	0	0	0	0	0	0	0	0	0	0	0	Receive Queue Pointer			
QSCI1TD	WO	F0005020	0	0	0	0	0	0	0	Transmit Data								
QSCI1RD0	RO	F0005024	0	0	0	WRAP	NF	FE	PF	Queued Receive Data #0								
			•															
QSCI1RD15	RO	F0005050	0	0	0	WRAP	NF	FE	PF	Queued Receive Data #15								

Figure 11: The SCI registers

Following below is a short description of each of these registers and how they are used, as presented in (QSCI Reference Manual, 2001).

- SCI1DR: This is the data register used in byte mode. It is used as a receive register when read and as a transmit register when written.
- SCI1SR: This is the register containing status bits for the communication when communicating in byte mode. It contains flags to monitor transmission, reception, line activities and message errors.
- SCI1CR: This is the control register of the SCI. It contains control bits to enable transmission/reception, loop-back from transmit to reception buffer, choice of parity and character length and enabling various interrupts.
- SCI1BRR: This register is used to set the Baud rate of the system, and must be written before any communication can start. The register is written with a suitable Baud rate divisor to obtain the desired Baud rate.
- QSCI1CR: This register controls the SCI when operating in buffered mode. It contains bits to enable buffered mode and the generation of various interrupts.
- QSCI1BD: This register is written with a value to determine how much delay should be inserted between transmitted bytes when operating in buffered mode. The delay is measured in (system clock / 1024). A delay might be necessary when communicating with slow devices.
- QSCI1SR: This register contains status bits for the buffered SCI. The bits show status of transmit and receive buffers and the logic level of transmit and receive pins.
- QSCI1RQP: This register contains the receive buffer pointer, which shows in what buffer position the next received byte will be placed.

- QSCI1TD: This register is the transmit buffer data input register. The register is written with a byte that should be transmitted, which is then transferred to the end of the transmit buffer.
- QSCI1RD0 -> QSCI1RD15: These sixteen registers are the receive-buffer data registers. They contain the most recent data that has been received on the serial port

Before the SCI can be used the control registers must be written to achieve the desired functionality, as mentioned above. This can be to choose between buffered or byte mode communication, setting the Baud rate, setting delay between bytes and of course enabling receive and transmit. For sending a byte you write that byte to a transmit register, and to receive a byte you read a reception register.

For our system the SCI's buffered mode was to be used. The RTEC has 16 receive registers and a 32 byte buffer for the transmitter. The latest received byte can be accessed with the help of the receive buffer pointer, which gives the location in the buffer where the next byte will be placed. Data is sent to the transmit buffer by writing the transmit buffer data input register.

The control register has bits that can be set to generate hardware interrupts to the APIC when various events occur. For our system the RBNFWE (Receive Buffer Near Full Warning Enable) bit was set to generate an interrupt when the number of bytes indicated by the value in RBNFC (Receive Buffer Near Full Count) had been received. This was later used for filling up a buffer needed for the communication protocol used by the ECU when requests for diagnostic services are received from external diagnostic tools.

5.3 Developed drivers for the SCI

Basic routines for initialising the SCI, changing Baud rate, sending/receiving characters and similar were developed, as well as some application specific routines that were aimed at the implementation of the communication protocol described in chapter 6.

During the work described in this report, the following drivers and functions were developed for the serial communication interface:

- init_ser_io: this routine is used to initialise the serial communication interface by enabling receive and transmit, setting the default Baud rate, setting the SCI to generate an interrupt when a character is received and enabling buffered mode.
- close_ser_io: this routine is used to close down the serial communication by disabling receive and transmit.
- set_baud_rate: this function can be used to set the Baud rate by passing the function a value for the Baud rate divisor register.
- select_baud_rate: this function is used to select the Baud rate by passing it one of the Baud rate constants that are defined in the program.
- put_char_b: this function is used to transmit a single one byte character on the serial port when the SCI is operating in byte mode.
- get_char_b: this function reads a single one byte character from the serial port when the SCI is operating in byte mode.
- put_str_b: this function is used to transmit a string on the serial port when the SCI is operating in byte mode.
- put_char: this function is used to transmit a single one byte character on the serial port when the SCI is operating in buffered mode.
- get_char: this function reads a single one byte character from the serial port, data register number zero, when the SCI is operating in buffered mode.
- put_str: this function is used to transmit a string on the serial port when the SCI is operating in buffered mode.
- read_char: this function reads the latest received byte on the serial port and thereafter decrements the receive buffer pointer when the SCI is operating in buffered mode.
- write_char: this function transmits a character on the serial port without checking for transmit buffer overflow when the SCI is operating in buffered mode.
- send_message: this function is used to transmit a message buffer on the serial port when the SCI is operating in buffered mode, it accepts a pointer to the buffer and the length of the buffer as arguments. It is used to send responses to commands that have been sent to the ECU.

These functions were then tested, as described in section 5.5, to make sure they operated correctly. The drivers implemented for this thesis were the ones that were considered useful for the project.

5.4 Connection to the PC

After the drivers for the serial communication interface had been written, it was necessary to make it possible to connect the ECU to other equipment, like for example a PC. This would allow for some real testing of the system to be performed, and of course later on it would also be necessary for the development of the control functionality.

To connect the LLIB SCI port to the PC it was necessary to build a converter to convert the signal produced by this board to a signal complying with the RS232 standard, as used by the PC serial port. Luckily enough there are integrated circuits available to do exactly this. The converter was built using a simple circuit consisting of a Motorola IC and four capacitors. The integrated circuit contains three pairs of receiver and transceiver pins, which are connected to data in and data out pins for the electronic boards. The four capacitors are needed to perform a voltage conversion from 5 volts as used by the LLIB to ±10 volts for the PC serial port. The RX/TX and DI/DO pins were soldered to a DB-9 connector and a 30-pin connector respectively, and electronics and PC were connected with a zero modem cable.

The schematic for this simple conversion circuitry is shown in figure 12 below.

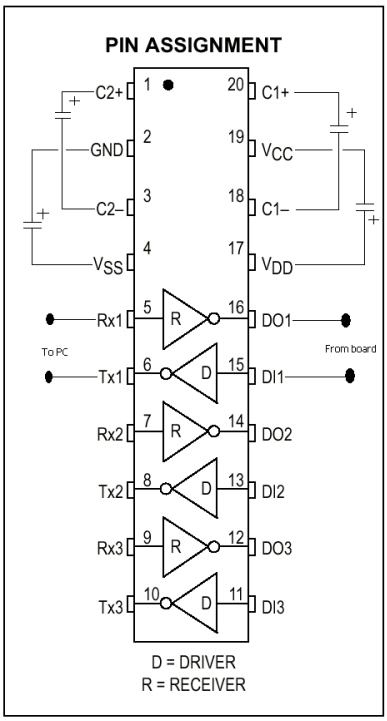


Figure 12: Schematic for the RS232 converter

A data sheet for the integrated circuit is included as an appendix.

5.5 Evaluation of the SCI routines

To begin with, some of the written routines had been tested simply by doing a loop-back on the port, that is the TX and RX pins were connected. After the RS232 converter had been built some more thorough testing could be performed with the help of the PC terminal program Hyperterminal. A test program was written to enable testing of the various functions that had been written, especially those that were supposed to be used for the communication protocol.

During the testing of the SCI some problems with the configuration of the RTEC were discovered. Because of faulty configuration files the RX pin was not operating correctly, meaning that nothing could be received on the system. Another problem was that the system clock could not be changed to a new value, but instead remained at the default value of 3 MHz, which is set at reset. Since the system clock sets a limit for the Baud rate, according to the following formula:

$$\text{Baud Rate} = \frac{\text{System Clock}}{2 \times 16 \times \text{SBRR}}$$

where SBRR is the value programmed to the Baud rate divisor register, this meant that there were problems communicating at the Baud rates needed by the communication protocol that was to be implemented.

These problems were later solved by doing adjustments to the RTEC and having new configuration files generated.

5.6 Comments on the developed SCI routines

As with the other functions of the RTEC the drivers for the SCI basically consists of writes to different control registers and reads of status bits in the status registers. This means that code development is quite easy. Unfortunately during the work some problems with the SCI functionality were encountered. For instance, as mentioned above, the port on the LLIB was at first not functioning the way it was supposed to.

To find out exactly what is causing problems when a program is not working correctly you preferably use the debugger that comes with the ARM software. By accessing the various

registers in the electronics you can check to see if some of them contain the wrong values or are not acting correctly. It is important to make sure that the methods you use to debug the software do not affect the behaviour of the system. If a problem with the functionality of the hardware is found, this can be solved by generating new configuration files for the FPGA:s.

The SCI routines that were developed were intended for the implementation of a diagnostic tool communication protocol. In the future it might turn out that more routines would be useful. Those routines could then probably easily be implemented, perhaps using some of the routines already developed. It is believed that all of the SCI functionality has now been tested and future code development in this area should be quite painless.

For a newer version of the LLIB an RS232 converter was added to the board itself, making the external converter unnecessary. The port on the LLIB can now send and receive signals that comply with the RS232 standard.

6 The Keyword Protocol 2000

This chapter describes the development of a communication protocol used for the communication between ECU:s and external diagnostic tools, the Keyword Protocol 2000 (KWP2000). The developed protocol uses the previously developed interrupt driven serial communication.

6.1 Definition of KWP2000

KWP2000 is a communication protocol that should be used by all DaimlerChrysler ECU:s with diagnostic capability. The protocol defines how the request and response messages that are sent between an ECU and an external diagnostic tool or between two ECU:s should look. The purpose of the protocol is to achieve standardisation of diagnostic feature content and diagnostic services. Figure 13 below shows how the format of a request message is defined in (Keyword Protocol 2000 Requirements Definition, 2001).

Data Byte #	Data Value Parameter	Parameter Description	Message Usage
1	**$XX**	**Request Service ID**	**Mandatory**
2	**$XX** $YY : $ZZ	**Parameter #1** Parameter value #1 : Parameter value #1	
3	**$XX** $YY : $ZZ	**Parameter #2** Parameter value #2 : Parameter #2 Value	
:	**:**	**:**	
n	**$XX** $YY : $ZZ	**Parameter #m** Parameter value #m : Parameter value #m	

Figure 13: Format for a KWP2000 request message

The first column of the table specifies the byte number that should be used for each parameter in the data stream. The data value is a hexadecimal value for service ID:s and parameters. The parameter description describes each parameter in the message. Message usage specifies if the parameter is considered to be mandatory, conditional or optional.

When an ECU receives a request to perform a certain service it should respond with either a positive or a negative response message, depending on if it can perform the requested service or not.

The format of a positive response message is shown in figure 14 below. Positive response can be sent to indicate that a request has been received, and is always sent to indicate that a requested service can be performed by the ECU.

Data Byte #	Data Value Parameter	Parameter Description	Message Usage
1	**Request Service ID + $40**	**Positive Response ID**	**Mandatory**
2	$XX	Parameter value #1	Conditional
:			
n	$XX	Parameter value #n-1	Conditional

Figure 14: Format for a KWP2000 positive response

The columns of this table are properly described by the description given above for the request message format. The first byte of the positive response is the service ID plus 0x40.

If a requested action can not be performed a negative response should be sent by the ECU. The first byte of the negative response message will always be $7F. This byte is followed by the service identifier of the requested action as well as a negative response code. The KWP2000 definition lists a number of different negative response codes that can be used for this message. The format of the negative response message is shown in figure 15 below.

Data Byte #	Data Value Parameter	Parameter Description	Message Usage
1	**$7F**	**Negative Response ID**	**Mandatory**
2	$XX	Request Service ID	Mandatory
3	$XX	Negative Response Code	Mandatory

Figure 15: Format for a KWP2000 negative response

Under some conditions there should be no positive or negative response sent by the ECU. The conditions for this are:

- The message indicates that no response is required.
- ECU diagnostics are functionally started, maintained and stopped.

The protocol uses diagnostic service identifiers (SID:s) to identify the different services supported by the protocol standard. The SID:s are hexadecimal values that are used for exchanging information between the ECU and an external tool or another ECU, reading trouble codes, controlling ECU operation or reading signal levels. The supported SID:s can be divided into five different groups according to their function. These groups are:

- Diagnostic Management: SID:s that are used for start, stop, altering or maintenance of diagnostic sessions.
- Data Transmission: SID:s for enabling an external tool to send, receive and alter data stored in an ECU.
- Input/Output Control: SID:s for enabling an external tool to control the states of I/O devices in an ECU.
- Remote Activation of Routine: SID:s used for starting or stopping a routine or for returning results from a routine.
- Upload/Download Control: SID:s that enable the external tool to demand data to be downloaded to the ECU or uploaded from the ECU to the external tool.

6.2 Implementation of the protocol

For the implementation of the protocol described above the previously developed routines for the APIC and the SCI were used. The system was designed to generate an interrupt every time a character was received on the serial port. This character is then placed in a message buffer. The first thing that is done after the reception of a complete message is a control that the message is a valid request message. This means checking that no unknown identifiers are being used, and it might also include determining whether or not the message has been corrupted during transmission. If the message is considered to be correct, a function is called for handling the request sent by the external diagnostic tool. This request handler decodes the received message and calls the appropriate SID handler function to determine if the requested service can be performed or not. If the service can be performed, code for servicing the request is executed and a positive response message is prepared. Otherwise a negative response message is prepared with the best suited negative response code. If the received message is considered to be incorrect in any way, no response should be sent. This will force a retransmission of the message.

After the handling of the received message has finished the program must wait until it is allowed to transmit the response, and then send it on the serial port. After the response has been sent the program goes back into a loop waiting for the reception of a new message. If no message is received within a certain period of time a timeout occurs, and a reset of the communication is performed by the ECU.

In figure 16 below there is a simple flowchart that describes how the program works.

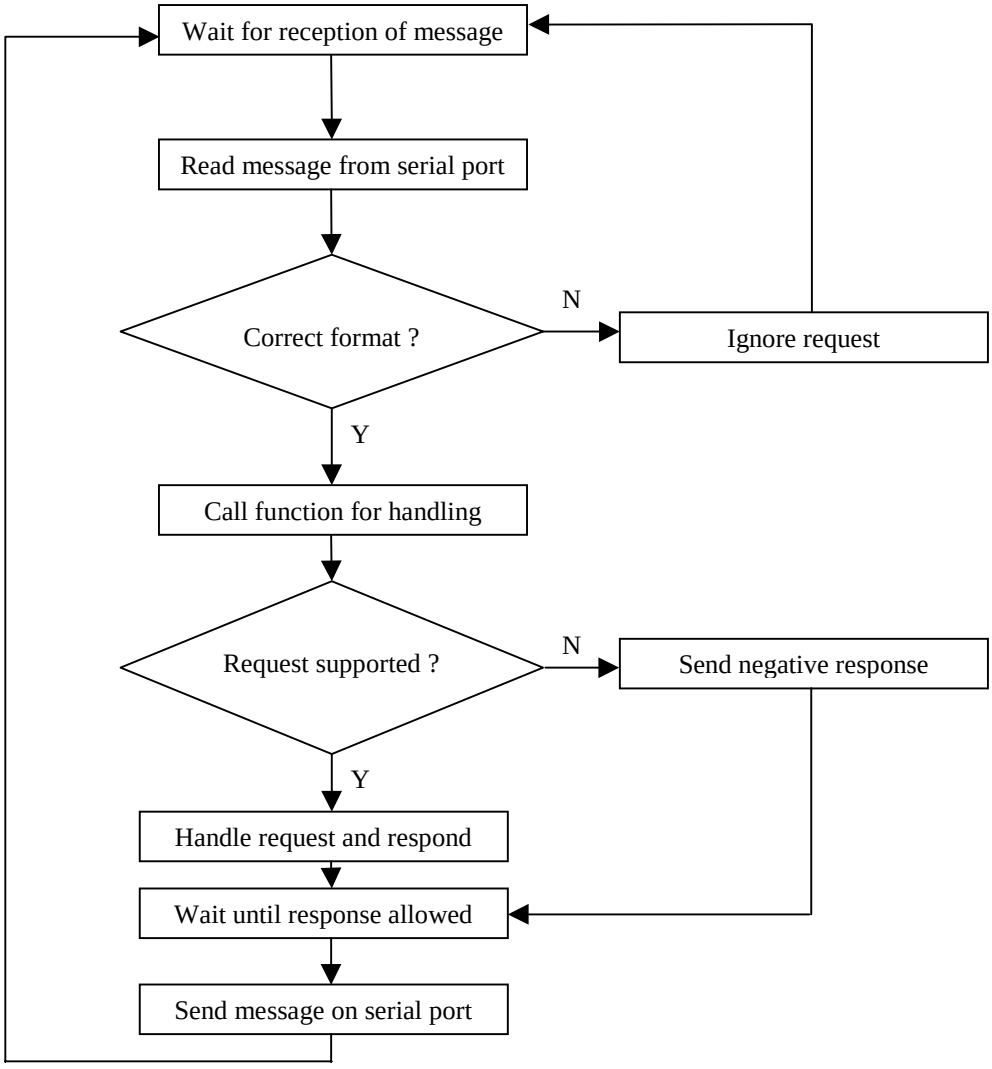


Figure 16: Flowchart for KWP2000

The definition of KWP2000 only covers how request and response messages should be formatted. Nothing is mentioned about how the communication in the system should be handled, this is something that might vary from system to system. Some of the things that you must consider are how the timing of the messages works, what kind of error protection should be used and what kind of additional information you have to transmit for the communication to work.

Great effort was put into implementing the protocol in such a way that it would be easy to extend it to support more functions or change the implementation of the already supported functions. Possible reasons for such changes could be changes to the ECU making it possible to support more of the services covered by the protocol definition, or changes to the protocol itself, making it necessary to change the implementation of protocol functions. These events are very likely to occur, since the development of this ECU has only just started.

The block schedule in figure 17 below shows the different components of the program and the connections between them.

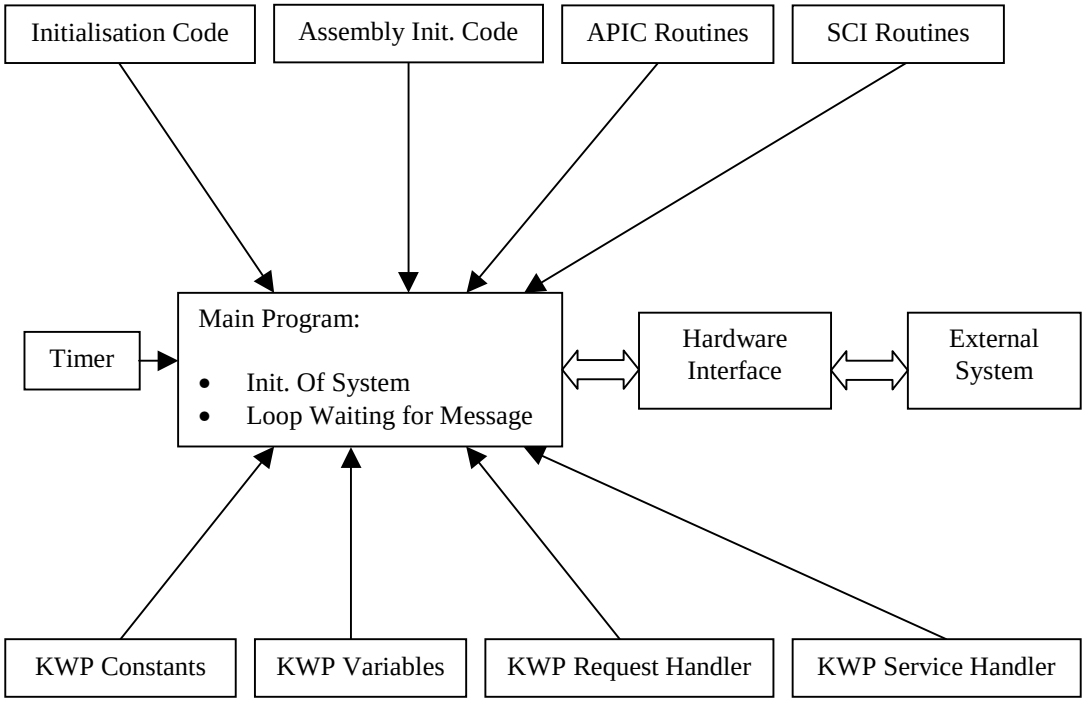


Figure 17: Components of the KWP2000 program

Following below is a list of the files in the project and a description of what they do.

- main.c: this file performs necessary initialisations, like initialising the apic and the sci and setting the system clock frequency to the correct value. After that it goes into an infinite loop, waiting for the reception of a character on the serial port.
- init.s: this file contains assembly code to initialise the system for the interrupt handling to work.

- system_init.c: this file contains code for setting the clock frequency and setting up the stack space, as well as initialising the interrupt handling and the serial communication interface.
- apic.c: this file contains functions needed for the interrupt handling to work.
- sci.c: this file contains the drivers for the serial communication interface.
- kwp.c: this file contains functions that handle the reception of a request message and the sending of a response message.
- kwp_services.c: this file contains the functions that carry out the requested services and format appropriate response messages.
- timer.c: this file contains the timer that is needed for the communication. How the timer should be configured depends on the system where the protocol is used. One example is given in the next chapter.
- kwp_constants.h: this file contains various constants that are needed for the protocol, for instance service identifiers and error codes.
- kwp_variables.c: this file contains variables that are needed for the protocol and the communication, for instance message buffers and status flags.
- IRQ_handlersx.s: each interrupt source has an IRQ handler to allow for re-entrant interrupts.

As previously mentioned some of the code is dependent of how communication is handled in the system.

6.3 Testing of the protocol with PC terminal program

At the time when the implementation of the protocol had been finished there was no real diagnostic tool available for testing the system. Instead a simple terminal program was created and used to simulate the communication between the ECU and a diagnostic tool.

In the department an older system using KWP2000 was available. This system had a function that could automatically generate log files of the communication between diagnostic tool and ECU. This function was used to generate log files that could serve as a basis for the testing of the developed system.

The communication part of the system had already been tested with the help of a normal PC terminal program. One problem when testing the protocol was that many of the hexadecimal values used by the protocol correspond to characters that can not be printed on the screen by

the terminal program, and can also not be entered from the keyboard. To get around this problem the terminal program first had to do a conversion of the received values, as well as converting entered values before transmission. This means that you convert a hexadecimal value to its corresponding ASCII character (0x0 converted to ’0’ and so on) and the other way around. With this functionality and the above mentioned log files it was possible for the terminal program to simulate the connection between ECU and diagnostic tool.

An example of one of the log files used is shown in figure 18 below.

```
>>>>>>>>>>>>>>>>>>>>>>>>>
Created by user: kaellst on computer: FTSTG3116 at Fri Aug 31 13:46:21.675 2001
driver: KWP2000 (build Oct 24 2000)
<<<<<<<<<<<<<<<<<<<<<<<<<

COM1 , baud: 10400 (8N1)

Fri Aug 31 13:46:27.363 2001
TxD: InitPattern 81 18 F1 81 0B

Fri Aug 31 13:46:27.473 2001
RxD: 80 F1 18 03 C1 DF 8F BB

Fri Aug 31 13:46:27.473 2001
TxD: 83 18 F1 10 86 04 26

Fri Aug 31 13:46:27.543 2001
RxD: 80 F1 18 02 50 86 61

baud: 57600 (8N1)

Fri Aug 31 13:46:27.563 2001
TxD: 82 18 F1 83 00 0E

Fri Aug 31 13:46:27.613 2001
RxD: 80 F1 18 02 7F 10 1A

Fri Aug 31 13:46:27.613 2001
TxD: 88 18 F1 3B FC 0F A0 00 90 41 00 48

Fri Aug 31 13:46:27.693 2001
RxD: 80 F1 18 04 7B FC 0F A0 B3
```

Figure 18: Example of a communication log file

The terminal program was created in Visual Basic, and it has the features necessary for the simulations. A simple graphical user interface was created to make it possible to open the serial port, set the Baud rate, send request messages and display the received responses. It was not possible to use all the Baud rates that are used by the protocol, since only a limited number of Baud rate values are allowed to be set from the Visual Basic application. Therefore some values had to be replaced with one of the available standard values. This minor change was not believed to be a problem.

Diagnostic requests were sent from the terminal program to the ECU by clicking a message button in the user interface, and the received response from the ECU could then be displayed, studied and verified against the correct response available in the log files. The diagnostic requests were made up of strings of bytes from the log files.

The result of this testing was that the program seemed to be working properly, at least as far as the formatting of the messages was concerned. Of course it could not yet be concluded that the current implementation would function correctly in a real system. For instance the terminal program had none of the timing functionality that a real system would have. Some further testing that was done to gain some knowledge in this area is described in chapter 7 of the thesis.

Figure 19 shows how the user interface of the program looks.

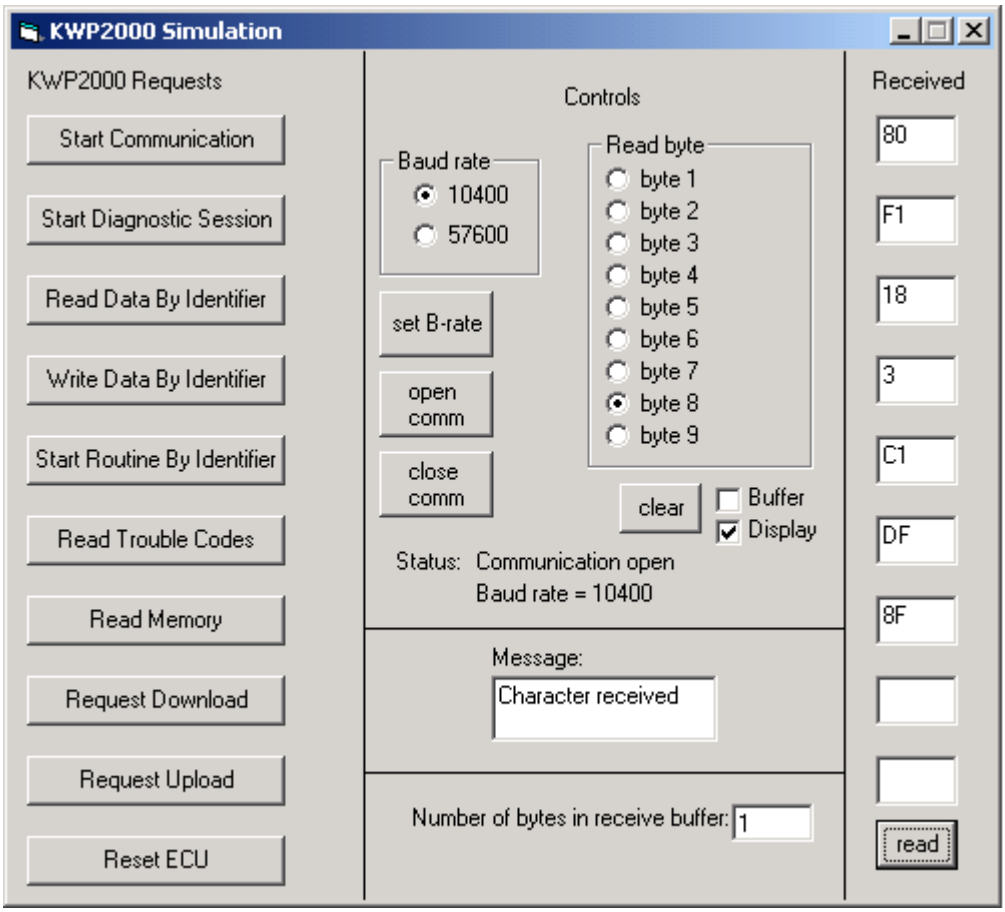


Figure 19: The user interface of the terminal program

To the left in the figure you can see the buttons used for sending request messages. In the middle there are some control functions as well as status displays. To the right of the figure the user can choose to display a number of bytes from the received response message.

6.4 Comments on the implementation of KWP2000

During the work on the protocol some problems were caused by the fact that it was somewhat unclear exactly how the implementation would have to be done in order to be compatible with other systems using the protocol. An implementation from an older system, a power PC based ECU, was available to give some guidance in that area.

The current ECU does not support all of the services that are handled by the protocol. In the future there might be a need to add support for more diagnostic services. This should then cause no problems. The implementation of the protocol can easily be extended by adding support for the new functions in the service handling part of the program. The communication part already supports requests for all of the services available in the latest protocol definition, so no changes would be necessary in that area of the program.

The simulation with the log files and the PC terminal program shows that the ECU can receive a request message formatted according to KWP2000, handle that request and send a response message formatted correctly. This would show that the implementation of the protocol had been done correctly. The simulation with the terminal program had not shown whether or not the timing functionality of the program was working correctly. To make sure that this was the case some further testing was performed, as described in the next chapter.

7 Adapting KWP2000 to MARC1

This chapter describes how the implemented system was tested and evaluated, which was done with the help of a software called MARC1. Some changes that had to be done to adapt the protocol implementation to this software are presented. A simple measurement and calibration application that was created is also described.

7.1 The MARC1 application system

The MARC1 application system is a software that can be used for performing measurements and calibrations on an ECU during the development. This software had previously been used in the department for the power PC based ECU development system. For the communication between the ECU and the software running on the PC various protocols can be used, for instance KWP2000. It was therefor thought that it would be a good idea to use it to test the developed software.

MARC1 can be used to put together a graphical measurement and calibration environment, to be used for evaluation of the ECU's performance. The configuration files needed to create an application can be generated automatically from a Simulink block-schedule. For the power PC based system control structures are created using Simulink blocks for the different functions of the ECU. The finished Simulink model can then be used to generate C code for the ECU and configuration files for the application system, which in turn can be used to create a measurement and calibration environment. This allows the user to easily and fast make changes to the system, without any detailed knowledge about programming the ECU or configuring the application system. It is desired to make this possible for the ARM based development system also.

Figure 20 shows how a typical development environment in the application system can look.

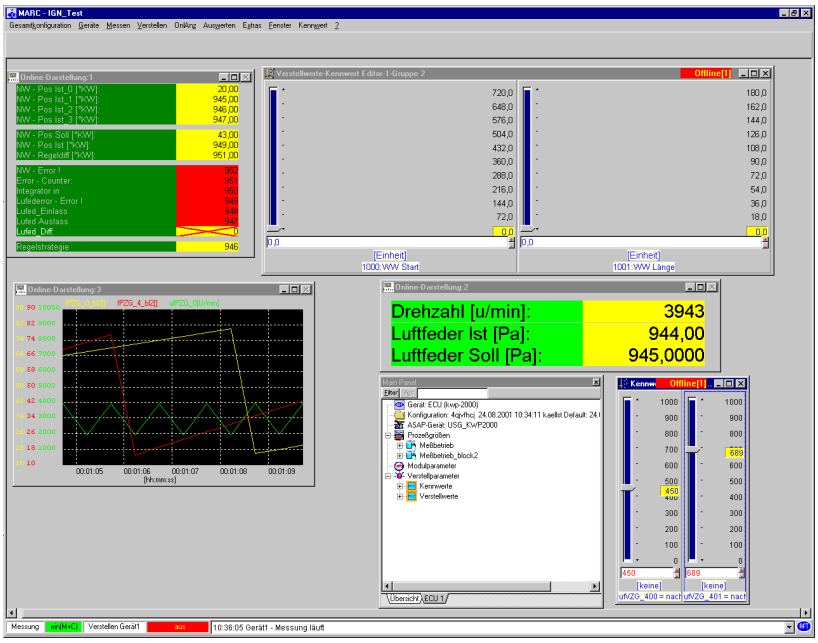


Figure 20: A MARC1 development environment

The sliders that are shown in the figure are used for calibration of the ECU, and the tables and the graph are used for displaying the measurement values sent by the ECU to the application tool.

The software is very simple to use, and it is also very flexible when changes have to be made. For most of the communication with the application tool services for reading and writing data are used. It is also necessary to use services for starting communication and diagnostic session, as well as services for synchronisation of the communication between the ECU and the application tool.

7.2 Modifications made to the program

For testing purposes an application was to be created in the MARC1 development environment. This application would consist of sliders to enter values to be sent to the ECU and some different ways to display measured values, like graphs and tables. As mentioned in chapter 6, KWP2000 does not define how the communication should be handled in the system. For the previously developed program to work correctly together with the MARC1 application it would be necessary to make some changes. What had to be handled were the header bytes used by the application system and the timing of the messages.

Figure 21 below shows how the messages sent between application system and ECU should look.

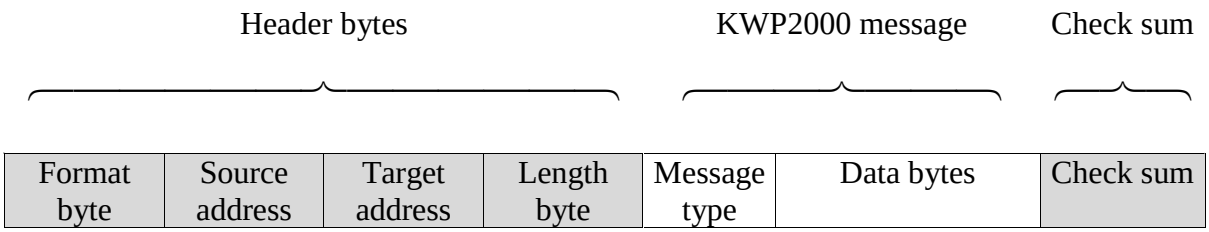


Figure 21: Format for KWP2000 messages

At the beginning of the message there are a number of header bytes. The first byte, the format byte, gives some information about the message and how it is formatted. For instance it contains information about whether or not the following three header bytes, source address, target address and length byte, are available. The first two bits of the format byte show what kind of addressing is used, while the remaining six bits either contain the length of the message, if no length byte is used, or are all zero, if a length byte is available in the message. This is shown in figure 22 below.

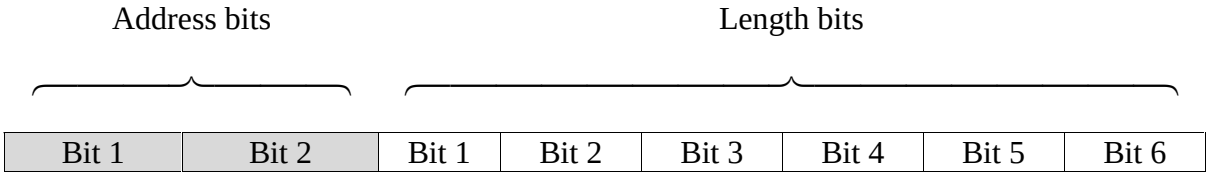


Figure 22: The bits of the format byte

After the header bytes you find the real KWP2000 message. The first byte of the message provides information about what kind of message it is. For request messages this is the service identifier, telling the ECU what service to perform. For response messages this byte indicates a positive or negative response. Following this byte are data bytes that are dependant on which service has been requested. Finally there is a checksum byte at the end of the message that can be used to determine if the message has arrived without being modified during the transmission.

The checksum is calculated by adding all the characters in the message. At the receiving end the checksum is once again calculated and compared to the checksum that has been received together with the message. If it turns out that the message is in some way incorrect the message will be ignored, and no response will be sent. This will force a retransmission of the message, which will then hopefully arrive in a correct format.

The code needed for handling the header bytes and the checksum had already been written for the test with the terminal program and the log files, as described in chapter 6, so no changes had to be made in that area of the program.

Something that had not yet been handled by the program was the timing of the messages sent. Since the application tool sends out a new request every 500 ms and does not accept a response until 20 ms after the last message byte has been sent, some kind of timer had to be added to the system. The timer would be used to make sure that the ECU sent a response message to a received request sometime between 20 ms and 500 ms after the reception of the last byte of the message, as shown in figure 23 below.

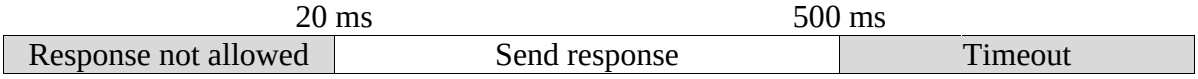


Figure 23: The timing of response messages

If 500 ms pass and a response has not yet been received by the application tool, a communication timeout will occur and a new message will be sent to the ECU. Similarly, if the ECU does not receive a request from the application tool before 5000 ms has passed there will be a timeout on the ECU side, and the protocol must be reset. This is because the Baud rate has to be changed if future messages shall be received correctly, and it is also necessary to reset some flags and counters.

To implement the timer one of the RTEC's PWM (Pulse Width Modulator) channels were used. This allows the programmer to make the ECU generate an interrupt every time a programmable number of system clock cycles has passed. There are two registers that have to be written to get the right timer period generated by the PWM channel, as described in (Pulse Width Modulator Reference Manual, 2001). You first write the prescale register with the number of system clocks that should be used for measuring the period. Then you write the desired period, in number of system clocks, to the period register. For everything to operate correctly it will also be necessary to write a value, smaller than the period, to the pulse width register. After the registers have been initialised in this manner you can write the PWM control register and enable the generation of an interrupt every time the PWM counter reaches the programmed period.

For our system the PWM was set to generate an interrupt every millisecond. For the timing of the communication on the serial port two counters were used. These were incremented every time the interrupt servicing routine of the PWM was called. When the last character of a request message was received one of the counters were reset. When it had once again reached 20 a flag was set in the interrupt servicing routine to let the system know that it was now allowed to send a response to the request. The 5000 ms counter was reset every time a character was received. If there was no character received for more than 5000 ms a routine was called to reset the protocol. As mentioned this reset operation involves setting flags and other variables to default values, as well as setting the Baud rate of the system to the default value of 10400.

7.3 A MARC1 application example

For evaluation purposes a simple application was put together in MARC1. This application consisted of elements enabling measurements, calibrations and access to look-up tables defined in the ECU. A screenshot of the application is shown in figure 20.

Each control in the application must be assigned an ID, which can then be sent to the ECU together with the request message to tell it what structure or what memory location in the ECU should be read or written. The assignment of ID:s is done in a configuration file, and together with the ID there is also information about what data types should be used, possible limits for values and dimensions if applicable. For configuration of MARC1 some of the configurations used for the power PC system were modified so that they would work together with the ARM based ECU.

The test application gives the user the possibility to perform measurements on some data structures in the ECU and have the read values presented in tables and graphs. When the user requests the start of a measurement by clicking the measurement button, this information is what is sent between the ECU and the application system.

```
>>>>>>>>>>>>>>>>>>>>>>>>>
Created by user: kaellst on computer: FTSTG3116 at Fri Aug 31 13:43:11.852 2001
driver: KWP2000 (build Oct 24 2000)
<<<<<<<<<<<<<<<<<<<<<<<<<

COM1 , baud: 10400 (8N1)

Fri Aug 31 13:43:14.706 2001
TxD: InitPattern 81 18 F1 81 0B
```

Fri Aug 31 13:43:14.816 2001
RxD: 80 F1 18 03 C1 DF 8F BB

Fri Aug 31 13:43:14.816 2001
TxD: 83 18 F1 10 86 04 26

Fri Aug 31 13:43:14.886 2001
RxD: 80 F1 18 02 50 86 61

baud: 57600 (8N1)

Fri Aug 31 13:43:14.906 2001
TxD: 82 18 F1 83 00 0E

Fri Aug 31 13:43:14.956 2001
RxD: 80 F1 18 02 7F 10 1A

Fri Aug 31 13:43:14.986 2001
TxD: 83 18 F1 21 FA 01 A8

Fri Aug 31 13:43:15.046 2001
RxD: 80 F1 18 3F 61 FA 01 2C 04 F5 44 00 80 00 44 00 C0 00 44 00 00 01 44 00 40 01 44 00 80 01 44 ...

Fri Aug 31 13:43:15.056 2001
TxD: 83 18 F1 21 FA 02 A9

Fri Aug 31 13:43:15.116 2001
RxD: 80 F1 18 3F 61 FA 02 00 00 50 42 00 C0 00 44 00 00 01 44 00 40 01 44 00 00 68 42 00 C0 01 44 ...

.
.
.

The first message that is sent (TxD) to the ECU is a request to start communication. If a positive response is received (RxD) the application requests a diagnostic session to be started. Then the Baud rate is changed, and the application sends a message to make sure that the ECU has changed Baud rate and the communication is still operating correctly. After these transmissions have been made the measurements can be performed. One measurement is made every 500 ms until the user ends the measurement session by going offline.

For the testing performed no real measurements were made. Instead the program was made to create data that could be transmitted when a measurement was requested by the application. It would be just as simple to fetch the measurement values from some register tied to one of the sensors in the engine.

For writing data to the ECU the application has two slider controls. Data can be sent either by simply clicking and moving the slider or by typing a value into the box at the bottom of the slider control. This can be used for calibration purposes during development. Before any values can be written the user must go online by clicking the calibration button. When this is

done the application first sends a request to the ECU to read the values currently stored in the available data structures, and displays these values on the controls in the user interface.

As previously mentioned, a look-up table was also implemented in the application and in the ECU. Look-up table blocks are available in Simulink for design of control structures. A look-up table is used to map a number of inputs to an output using linear interpolation. For the test application a 2D look-up table was used. This block has two inputs and one output. Two vectors, corresponding to x and y axes, are defined, and for each pair of values in these two vectors a data value is assigned. If two input values to the look-up table matches row and column parameters the output will be the data value at the intersection of the row and column, otherwise an interpolation will be performed. The look-up table is defined in the ECU as the following data structure:

```
typedef struct CHARAC_2DIM_FIELD_FLOAT_Tag
{
        float x[11];
        float y[11];
        float data[121];
}CHARAC_2DIM_FIELD_FLOAT;
```

The program initialises this structure to some suitable values at the start-up of the system, and the data values can then be changed from the graphical user interface, either by entering the value in a table or by clicking and dragging 2D or 3D graphs. Figure 24 shows how the look-up table is presented in the MARC1 application system, as a 3D graph and a simple table.

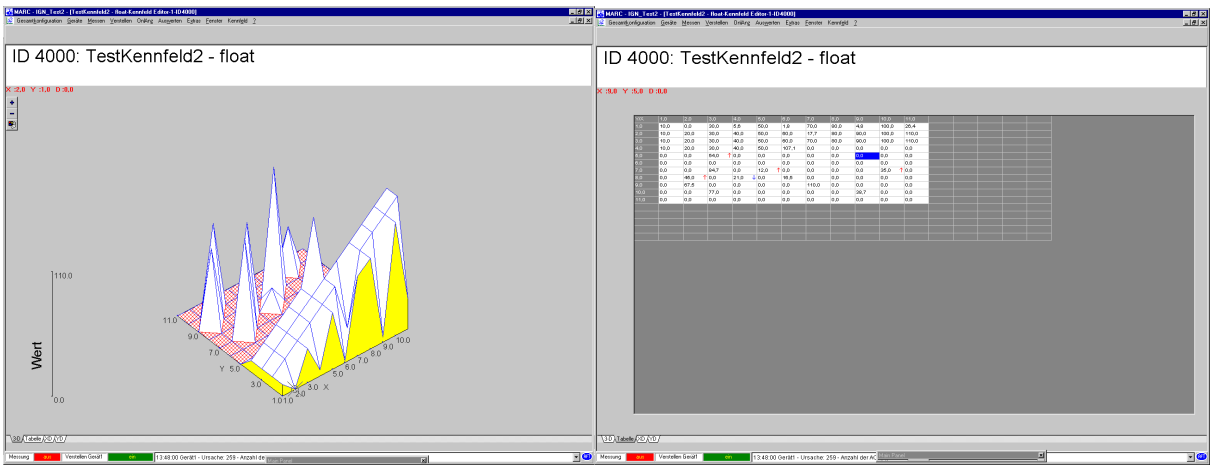


Figure 24: Look-up tables in MARC1

When the values of the look-up table are changed, the application sends a request to the ECU to update the affected data structures. This communication looks the following way when the value 65 is written to x-position 7 and y-position 5.

```
>>>>>>>>>>>>>>>>>>>>>>>>
Created by user: kaellst on computer: FTSTG3116 at Fri Aug 31 13:46:21.675 2001
driver: KWP2000 (build Oct 24 2000)
<<<<<<<<<<<<<<<<<<<<<<<<

COM1 , baud: 10400 (8N1)

Fri Aug 31 13:46:27.363 2001
TxD: InitPattern 81 18 F1 81 0B

Fri Aug 31 13:46:27.473 2001
RxD: 80 F1 18 03 C1 DF 8F BB

Fri Aug 31 13:46:27.473 2001
TxD: 83 18 F1 10 86 04 26

Fri Aug 31 13:46:27.543 2001
RxD: 80 F1 18 02 50 86 61

baud: 57600 (8N1)

Fri Aug 31 13:46:27.563 2001
TxD: 82 18 F1 83 00 0E

Fri Aug 31 13:46:27.613 2001
RxD: 80 F1 18 02 7F 10 1A

Fri Aug 31 13:46:27.613 2001
TxD: 88 18 F1 3B FC 0F A0 00 90 41 00 48

Fri Aug 31 13:46:27.693 2001
RxD: 80 F1 18 04 7B FC 0F A0 B3
```

The first three messages are used to establish stabile communication, as for the measurement operation described above. Then the actual writing to the look-up table is performed (TxD: 88 18 F1 3B FC 0F A0 00 90 41 00 48). The value 90 is the offset from the start of the look-up table structure in the ECU corresponding to the x and y coordinates, and 41 is the hex-value for 65.

7.4 Testing the application

During testing there were at first some problems with values not showing correctly during measurements and calibrations. For the configuration of these services the same kind of configurations as for the power PC based system had been used. It turned out that the problem was that this system and the ARM based system uses different byte ordering. The ARM system uses little endian byte ordering, while the power PC system uses big endian byte ordering. Since the configurations also contain limits for what values are allowed, this meant

that some values were set to zero because they exceeded the limit, and the values that were left unaltered still did not show up correctly. By modifying the configurations this problem was removed.

Another thing that was discovered was that the application system uses two byte integers while the ARM system uses four byte integers. This caused the wrong number of values to be transmitted during measurements when the values were declared as integers. This was simply solved by changing the data types of the variables in the ARM system from integer to short integer.

One known problem is that the system currently can not handle large look-up tables. If the data of the table require more than 245 bytes of memory, there would be a need for the application to send repeated requests to read the whole look-up table from the ECU. This is because the communication buffer can not hold more data than that. Currently this is not working correctly. The application system will only send one read request, even if that is insufficient to transfer the whole look-up table. This is believed to be caused by the application system and not by the protocol implementation. The reason for the problem is probably a faulty driver.

After the necessary changes had been made the application was running smoothly and could be used to perform measurements and write data to the ECU. The measurements were set to take place every 500 ms. This is the frequency that had been used for measurements on the older development system. Some measurements were made with the help of an oscilloscope to determine how much time the ECU needed to handle the requests currently used. One of the RTEC's general purpose input/output channels, as described in (General Purpose Input/Output Reference Manual, 2001), was used to toggle a pin on the LLIB at the start and theend of the request handling in the ECU, thereby creating a waveform on the oscilloscope that could be used to measure the time needed for processing. This test showed that the ECU currently needs significantly less than 20 ms to handle the requests. Since 20 ms is the time the ECU must wait before responding to a request, this means that it is this time that limits the possible frequency of measurements.

7.5 Comments on adapting KWP2000 to MARC1

By setting up some simple functions in the MARC1 application system the implementation of the protocol has been tested and is now working correctly, except for the handling of large look-up tables. It is believed that a faulty driver is causing problems when handling these structures. Some modifications had to be made to the program, like adding a timer function. The simple formatting of the messages had previously been tested with the PC terminal program and, as thought, this part of the program did no need to be modified.

The current system is very simple and basically only consists of some drivers for the SCI and the implementation of KWP2000. In the future, when more functions are added, it will be important to make sure that the timing of the protocol is not disturbed. If for instance more interrupt sources are added, these must be assigned the right priority so that they do not cause the timers to stop working. If this would mean that the timing functionality would have to be implemented in some other way, there would probably still be no need to do any changes to the main part of the protocol. Also when more functions are added to the protocol implementation the same precautions have to be taken to make sure that the communication remains stabile.

8 Conclusions and suggestions for the future

This chapter comments on the values and the shortcomings of the software developed. Suggestions are also given for how development could proceed in the future and how the software could be improved.

8.1 The developed software

Due to some time consuming hardware problems that had to be solved, not all of the planned work could be completed. It is still believed though, that this work has to some extent paved the way for future development on the system.

Drivers for the serial communication interface have been developed and tested, and communication with external devices now operates correctly. The SCI routines will probably be useful in the future, and new ones can easily be developed now that the hardware has been fully tested and is considered to be fully functioning.

The APIC was used for the implementation of interrupt driven serial communication and an interrupt driven timer. The developed APIC routines show how to set up the system in order for the interrupt handling to work. They also show how the future interrupt servicing routines for the other interrupt sources should be written. This will probably be helpful for other developers.

The implemented communication protocol was tested using the MARC1 application system, and is believed to be functioning correctly. The testing performed with the Visual Basic terminal program, though somewhat theoretical, should also show that the services not requested by the measurement application have been implemented correctly.

8.2 Suggestions for further development

The developed communication protocol has been tested using the MARC1 application system, creating a simple measurement and calibration application. Hopefully this test is enough to show that the implementation is fully functioning, and if problems would still arise

in the future it is thought that only minor changes would have to be done to get a fully functioning system. During the testing one problem was discovered when reading large data structures in the ECU. This is believed to be caused by the application system and not by the software running on the ECU system. To gain certain knowledge in this area it will be necessary to do some more testing of this functionality in the future.

The ECU currently only supports a small subset of the requests covered by KWP2000. In the future it might be necessary to add support for additional services, which could easily be done by adding appropriate code fragments to the service handling part of the protocol implementation.

To reduce the number of interrupts that are being generated the timer could be changed. It currently generates an interrupt every ms, but it would be possible to change this to have it generate an interrupt every 20 ms, thus reducing the number of timer interrupts by a factor twenty. The reception of messages could also be changed to reduce the number of interrupts for this purpose. Currently an interrupt is generated every time a character is received. This could be changed by letting the program check the first byte of the received message to see how many bytes must be received, and then setting the RBNFC bits in the buffered SCI control register to have an interrupt generated when the whole message has been received. Something that must be considered in that case is the fact that some messages will contain more than sixteen bytes, and will therefor not fit in the receive buffer. In those situations an interrupt would have to be generated each time the buffer was full. When changing Baud rate the program currently must wait for a while to make sure that the transmit buffer is empty before the Baud rate is changed. This means that the program will be halted for a while, which of course is not so good. It is therefor desired to make changes to eliminate this problem.

A new version of the program that solves the problems with the timer interrupts and the Baud rate change was actually written. This program generates a timer interrupt every 20 ms and uses a counter to decide when enough time (presently between 40 and 60 ms) has passed for the Baud rate change to be made. Since the license for the application system had expired this program could only be tested with the PC terminal program, and it is therefor not certain that it would work with the application system. This is something that must be determined in the future, and possibly some modifications to this program must be made.

The developed routines for the APIC can be used in the future when more of the ECU functions are implemented, and more interrupt sources are added to the system. This could be done by simply using the developed routines for enabling and configuring the needed interrupt sources, or the developed code could be used as a template to develop new routines more suitable for a certain usage. This part of the system is thought to have been fully tested at the completion of this work.

The developed and tested serial port connection to the PC could probably be used in the future for sending commands to the system when testing and evaluating new functions that have been developed. If more routines would be needed these could easily be implemented, possibly by using the routines already developed or by using them as guidance.

8.3 Evaluation of the development system

During the work some problems were encountered with the hardware. It was not always as simple as it should be to do development. The reason for this is that the system is very new and has not yet been fully tested, and therefor some problems are likely to be encountered. During the future development on the system, when other functionality of the ECU is used, other problems might very well occur and have to be dealt with.

It is believed though, that when the system has matured and when it has been fully tested it will probably allow developers to do fast ECU development. The RTEC will allow for very fast development of new drivers and the ARM based system will allow for very flexible adjustment of the hardware. By using Matlab, Simulink and Real-Time Workshop for the development of control algorithms this can also be done in a very fast and efficient way. The MARC1 application system and Real-Time Workshop will also allow people to work with ECU and engine development without knowing how to perform software development for the system. Putting these parts together and getting them to work properly will provide a great system for the development and testing of new engine control functions.

8.4 Conclusions

Even though not as much of the work as desired could be completed, the work on this thesis has still provided some valuable insight into close to hardware programming and development of engine control systems. It has also been an opportunity to practice a kind of practical

problem solving that is not often encountered at the university. Hopefully the completed work will be useful for the people who will be working with the same system and the same tools in the future.

References

APIC Reference Manual 0.2,
AIEC, 2001

ARM Developer Suite Version 1.1 Developer Guide,
ARM, 2000

Bilting U. & Skansholm J.,
Vägen till C, 3rd ed.,
Studentlitteratur, ISBN 91-44-01468-6, 2000

Burns A. & Wellings A.,
Real-time systems and programming languages, 2nd ed.,
Addison-Wesley, ISBN 0-201-40365-X, 1997

DCRTEC Reference Manual 0.2,
AIEC, 2001

ENCORE Reference Manual 0.3,
AIEC, 2001

General Purpose Input/Output Reference Manual,
AIEC, 2001

Gupta R. K.,
Co-Synthesis of Hardware and Software for Digital Embedded Systems,
Kluwer Academic Publishers, ISBN 0792396138, 1995

Keyword Protocol 2000 Requirements Definition,
DaimlerChrysler, 2001

Kiencke U. & Nielsen L.,
Automotive control systems for engine, driveline, and vehicle,
Springer-Verlag, ISBN 3-540-66922-1, 2000

Pulse Width Modulator Reference Manual,
AIEC, 2001

QSCI Reference Manual,
AIEC, 2001

Roos O.,
Grundläggande datorteknik,
Studentlitteratur, ISBN 91-44-46651-X, 1995

Schilling D. L. & Belove C.,
Electronic circuits, discrete and integrated, 3rd ed.,
McGraw-Hill, ISBN 0-07-055348-3, 1989

APPENDIX A: VB code

```
Private Sub Change_Baud_Rate_Click()

'set new Baud rate
If Option1.Value = True Then
MSComm1.Settings = "9600,N,8,1"
Option2.Value = True
Label3.Caption = "Baud rate = 10400"
Text14.Text = "Set B-rate = 10400"
ElseIf Option2.Value = True Then
MSComm1.Settings = "57600,N,8,1"
Option1.Value = True
Label3.Caption = "Baud rate = 57600"
Text14.Text = "Set B-rate = 57600"
End If

End Sub
```

```
Private Sub Open_Comm_Click()

If MSComm1.PortOpen = False Then
'open comm port 1
MSComm1.CommPort = 1
MSComm1.Settings = "9600,N,8,1"
MSComm1.PortOpen = True

'change status messages
Label11.Caption = "Communication open"
Text14.Text = "Comm opened"
Else
Text14.Text = "Comm already open"
End If

End Sub
```

```
Private Sub Close_Comm_Click()

If MSComm1.PortOpen = True Then
'close port 1
MSComm1.PortOpen = False

'change status messages
Label11.Caption = "Communication closed"
Text14.Text = "Comm closed"
Else
Text14.Text = "Comm already closed"
End If
```

```
End Sub

Private Sub MSComm1_OnComm()

If MSComm1.CommEvent = comEvReceive Then
Text14.Text = "Character received"
MSComm1.RThreshold = 0
End If

End Sub

Private Sub Clear_Display_Click()

'Clearing the display
If Check2.Value = 1 Then
Text7.Text = ""
Text8.Text = ""
Text9.Text = ""
Text10.Text = ""
Text11.Text = ""
Text12.Text = ""
Text13.Text = ""
Text2.Text = ""
Text3.Text = ""
Option3.Value = True
Text14.Text = "Receive fields cleared"
End If

'Clearing the receive buffer
If Check1.Value = 1 Then
MSComm1.InBufferCount = 0
Text1.Text = 0
End If

End Sub

Private Sub Read_Bytes_Click()

number_of_bytes = MSComm1.InBufferCount

If Option3.Value = True And number_of_bytes > 0 Then
Text7.Text = Hex(Asc(MSComm1.Input))
Option4.Value = True
number_of_bytes = number_of_bytes - 1
Text1.Text = number_of_bytes
ElseIf Option4.Value = True And number_of_bytes > 0 Then
Text8.Text = Hex(Asc(MSComm1.Input))
Option5.Value = True
number_of_bytes = number_of_bytes - 1
Text1.Text = number_of_bytes
ElseIf Option5.Value = True And number_of_bytes > 0 Then
```

```
Text9.Text = Hex(Asc(MSComm1.Input))
Option6.Value = True
number_of_bytes = number_of_bytes - 1
Text1.Text = number_of_bytes
ElseIf Option6.Value = True And number_of_bytes > 0 Then
Text10.Text = Hex(Asc(MSComm1.Input))
Option7.Value = True
number_of_bytes = number_of_bytes - 1
Text1.Text = number_of_bytes
ElseIf Option7.Value = True And number_of_bytes > 0 Then
Text11.Text = Hex(Asc(MSComm1.Input))
Option8.Value = True
number_of_bytes = number_of_bytes - 1
Text1.Text = number_of_bytes
ElseIf Option8.Value = True And number_of_bytes > 0 Then
Text12.Text = Hex(Asc(MSComm1.Input))
Option9.Value = True
number_of_bytes = number_of_bytes - 1
Text1.Text = number_of_bytes
ElseIf Option9.Value = True And number_of_bytes > 0 Then
Text13.Text = Hex(Asc(MSComm1.Input))
Option10.Value = True
number_of_bytes = number_of_bytes - 1
Text1.Text = number_of_bytes
ElseIf Option10.Value = True And number_of_bytes > 0 Then
Text2.Text = Hex(Asc(MSComm1.Input))
Option11.Value = True
number_of_bytes = number_of_bytes - 1
Text1.Text = number_of_bytes
ElseIf Option11.Value = True And number_of_bytes > 0 Then
Text3.Text = Hex(Asc(MSComm1.Input))
Option3.Value = True
number_of_bytes = number_of_bytes - 1
Text1.Text = number_of_bytes
End If

End Sub
```

```
Private Sub Start_Communication_Click()

'Start KWP2000 communication
If MSComm1.PortOpen = True Then
MSComm1.Output = Chr(&H81)
MSComm1.Output = Chr(&H18)
MSComm1.Output = Chr(&HF1)
MSComm1.Output = Chr(&H81)
MSComm1.Output = Chr(&HB)
MSComm1.RThreshold = 1
Text14.Text = "Message sent"
Else
Text14.Text = "Open comm first"
```

```
End If

End Sub

Private Sub Start_Routine_By_Identifier_Click()

'Start routine by local identifier
If MSComm1.PortOpen = True Then
MSComm1.Output = Chr(&H82)
MSComm1.Output = Chr(&H18)
MSComm1.Output = Chr(&HF1)
MSComm1.Output = Chr(&H31)
MSComm1.Output = Chr(&H1)
MSComm1.Output = Chr(&HBD)
MSComm1.RThreshold = 1
Text14.Text = "Message sent"
Else
Text14.Text = "Open comm first"
End If

End Sub

Private Sub Read_Memory_Click()

'Read memory by address
If MSComm1.PortOpen = True Then
MSComm1.Output = Chr(&H85)
MSComm1.Output = Chr(&H18)
MSComm1.Output = Chr(&HF1)
MSComm1.Output = Chr(&H23)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H1)
MSComm1.Output = Chr(&HB2)
MSComm1.RThreshold = 1
Text14.Text = "Message sent"
Else
Text14.Text = "Open comm first"
End If

End Sub

Private Sub Request_Download_Click()

'Request download
If MSComm1.PortOpen = True Then
MSComm1.Output = Chr(&H88)
MSComm1.Output = Chr(&H18)
MSComm1.Output = Chr(&HF1)
MSComm1.Output = Chr(&H34)
```

```
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H1)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H1)
MSComm1.Output = Chr(&HC7)
MSComm1.RThreshold = 1
Text14.Text = "Message sent"
Else
Text14.Text = "Open comm first"
End If

End Sub
```

```
Private Sub Request_Upload_Click()

'Request upload
If MSComm1.PortOpen = True Then
MSComm1.Output = Chr(&H88)
MSComm1.Output = Chr(&H18)
MSComm1.Output = Chr(&HF1)
MSComm1.Output = Chr(&H35)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H1)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H1)
MSComm1.Output = Chr(&HC8)
MSComm1.RThreshold = 1
Text14.Text = "Message sent"
Else
Text14.Text = "Open comm first"
End If

End Sub
```

```
Private Sub Write_Data_By_Identifier_Click()

'Write data by local identifier
If MSComm1.PortOpen = True Then
MSComm1.Output = Chr(&H88)
MSComm1.Output = Chr(&H18)
MSComm1.Output = Chr(&HF1)
MSComm1.Output = Chr(&H3B)
MSComm1.Output = Chr(&HFC)
MSComm1.Output = Chr(&H1)
MSComm1.Output = Chr(&H90)
```

```
MSComm1.Output = Chr(&H42)
MSComm1.Output = Chr(&HC8)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H63)
MSComm1.RThreshold = 1
Text14.Text = "Message sent"
Else
Text14.Text = "Open comm first"
End If

End Sub
```

```
Private Sub Start_Diagnostic_Session_Click()

'Start diagnostic session
If MSComm1.PortOpen = True Then
MSComm1.Output = Chr(&H83)
MSComm1.Output = Chr(&H18)
MSComm1.Output = Chr(&HF1)
MSComm1.Output = Chr(&H10)
MSComm1.Output = Chr(&H86)
MSComm1.Output = Chr(&H4)
MSComm1.Output = Chr(&H26)
MSComm1.RThreshold = 1
Text14.Text = "Message sent"
Else
Text14.Text = "Open comm first"
End If

End Sub
```

```
Private Sub Read_Data_By_Identifier_Click()

'Read data by local identifier
If MSComm1.PortOpen = True Then
MSComm1.Output = Chr(&H84)
MSComm1.Output = Chr(&H18)
MSComm1.Output = Chr(&HF1)
MSComm1.Output = Chr(&H21)
MSComm1.Output = Chr(&HFC)
MSComm1.Output = Chr(&H1)
MSComm1.Output = Chr(&H90)
MSComm1.Output = Chr(&H3B)
MSComm1.RThreshold = 1
Text14.Text = "Message sent"
Else
Text14.Text = "Open comm first"
End If

End Sub
```

```
Private Sub Reset_ECU_Click()

'ECU reset
If MSComm1.PortOpen = True Then
MSComm1.Output = Chr(&H82)
MSComm1.Output = Chr(&H18)
MSComm1.Output = Chr(&HF1)
MSComm1.Output = Chr(&H11)
MSComm1.Output = Chr(&H1)
MSComm1.Output = Chr(&H9D)
MSComm1.RThreshold = 1
Text14.Text = "Message sent"
Else
Text14.Text = "Open comm first"
End If

End Sub
```

```
Private Sub Read_Troube_Codes_Click()

'Read status of diagnostic trouble codes
If MSComm1.PortOpen = True Then
MSComm1.Output = Chr(&H83)
MSComm1.Output = Chr(&H18)
MSComm1.Output = Chr(&HF1)
MSComm1.Output = Chr(&H17)
MSComm1.Output = Chr(&H0)
MSComm1.Output = Chr(&H1)
MSComm1.Output = Chr(&HA4)
MSComm1.RThreshold = 1
Text14.Text = "Message sent"
Else
Text14.Text = "Open comm first"
End If

End Sub
```

APPENDIX B: RS232 converter data-sheet

MOTOROLA
SEMICONDUCTOR TECHNICAL DATA

Order this document
by MC145407/D

MC145407

Advance Information

5 Volt Only Driver/Receiver

EIA–232–E and CCITT V.28

The MC145407 is a silicon–gate CMOS IC that combines three drivers and three receivers to fulfill the electrical specifications of EIA–232–E and CCITT V.28 while operating from a single + 5 V power supply. A voltage doubler and inverter convert the + 5 V to ± 10 V. This is accomplished through an on–board 20 kHz oscillator and four inexpensive external electrolytic capacitors. The three drivers and three receivers of the MC145407 are virtually identical to those of the MC145406. Therefore, for applications requiring more than three drivers and/or three receivers, an MC145406 can be powered from an MC145407, since the MC145407 charge pumps have been designed to guarantee ± 5 V at the output of up to six drivers. Thus, the MC145407 provides a high–performance, low–power, stand–alone solution or, with the MC145406, a + 5 V only, high–performance two–chip solution.

Drivers

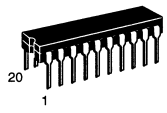
- ± 7.5 V Output Swing
- 300 Ω Power–Off Impedance
- Output Current Limiting
- TTL and CMOS Compatible Inputs
- Slew Rate Range Limited from 4 V/μs to 30 V/μs

Receivers

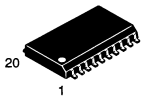
- + 25 V Input Range
- 3 to 7 kΩ Input Impedance
- 0.8 V Hysteresis for Enhanced Noise Immunity

Charge Pumps

- + 5 V to ± 10 V Dual Charge Pump Architecture
- Supply Outputs Capable of Driving Three On–Chip Drivers and Three Drivers on the MC145406 Simultaneously
- Requires Four Inexpensive Electrolytic Capacitors
- On–Chip 20 kHz Oscillator



P SUFFIX
PLASTIC DIP
CASE 738

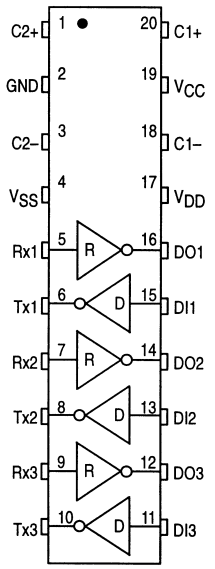


DW SUFFIX
SOG PACKAGE
CASE 751D

ORDERING INFORMATION

MC145407P	Plastic DIP
MC145407DW	SOG Package

PIN ASSIGNMENT



D = DRIVER
R = RECEIVER

This document contains information on a new product. Specifications and information herein are subject to change without notice.

REV 1
10/95

MOTOROLA