Tutorial Development Kit for 32-bit ARM Microcontrollers with a Focus on Multimedia

T. Sysala, P. Neumann, J. Pribyslavsky, M. Adamek

***Abstract*—** The article describes design and realization of a 32bit ARM core microcontroller development kit. The ARM Cortex-M3 architecture with LPC1769 microcontroller is described in more details aimed at the individual blocks. The LPC1769 microcontroller potentiality is demonstrated on internal communication variants, interrupt management and memory mapping philosophy. The real time operation system is also mentioned together with its various functions application benefits. The final solution is applicable in a laboratory for students enrolled for Microcomputers subject where programming and peripheral control is taught. That microcontroller kit is also possible to be employed as a cheap controlling device in various automation areas. As the development kit comprise even the network connection possibility, color display, and audio output, it can serve as a cost effective alternative for multimedia application development tool well comparable with many mobile phone applications.

***Keywords*—**Microcontroller, ARM, process control, education, development kit, multimedia.

I. Introduction

MICROCOMPUTERS and microcontrollers constitute a common ingredient in our daily life. We are meeting them without noticing it.

Microcomputers as a cheap and small form of digital devices (computers) lived through their rapid development in early 80-ties of the last century. Those microcomputers were first in 8-bit version and later in 16-bit version then. The model Intel8080 [1] and/or Zilog Z80 [2] may be mentioned as the most popular models at that time.

Microcomputers in 32-bit version with the ARM core gained popularity in more challenging application during 90ties of the last century [16].

II. Goal and Specifications

Many subjects taught at Tomas Bata University, Faculty of Applied Informatics, are oriented at technological processes control. The microcomputer presents one of alternatives for such processes control.

The goal of one our project was to design a development kit based on a 32-bit microcontroller with the ARM core which should comply with following requirements:

- Low costs,
- Extended peripheral equipment for interfacing technological processes,
- Extended peripheral equipment for various communication modes,
- Audio codec,
- Colour display.

III. The Architecture Selection

There were two fitting architectures, optionally also with relevant microcontroller type, for our design, namely ARM7TDMI and ARM Cortex-M3 architectures.

In spite of the fact that we can find processors with the ARM7TDMI core in millions device throughout the World, that architecture dated to 1994 is declining, and the ARM company itself is not recommending it for new designs [3]. The Cortex-M3 architecture is its successor.

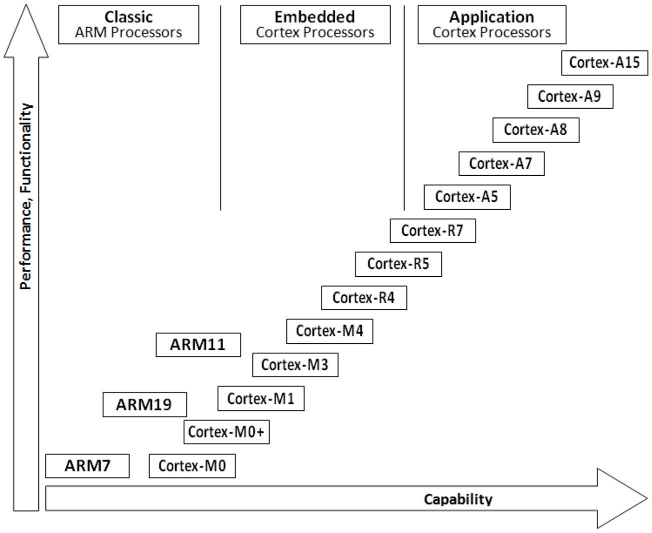

Fig. 1 Comparison of ARM architectures [10]

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The most remarkable difference lies in the fact that ARM7TDMI is based on the von Neumann architecture while Cortex-M3 is based on the Harvard architecture. From the practical point of view, the Cortex-M3 higher efficiency is related to its 1.25 DMIPS/MHz unlike the ARM7TDMI which offers only 0.95 DMIPS/MHz. The energy consumption comparison also favours the Cortex-M3 with 0.19mW/MHz unlike the ARM7TDMI with 0.28mW/MHz.

The Cortex-M3 architecture disposes of many remarkable features. Among the others, we can mention the program branching prediction, the interrupt faster response (12 clock cycles vs. 24-42 clock cycles at ARM7TDMI), hardware implemented advanced debugging interface, reduced energy consumption modes, and a sophisticated memory lock system.

There is a more detailed description of both architectures differences in the ARM company official report [4].

All above mentioned qualities have influenced the final ARM Cortex-M3 architecture selection with LPC1769 microcontroller.

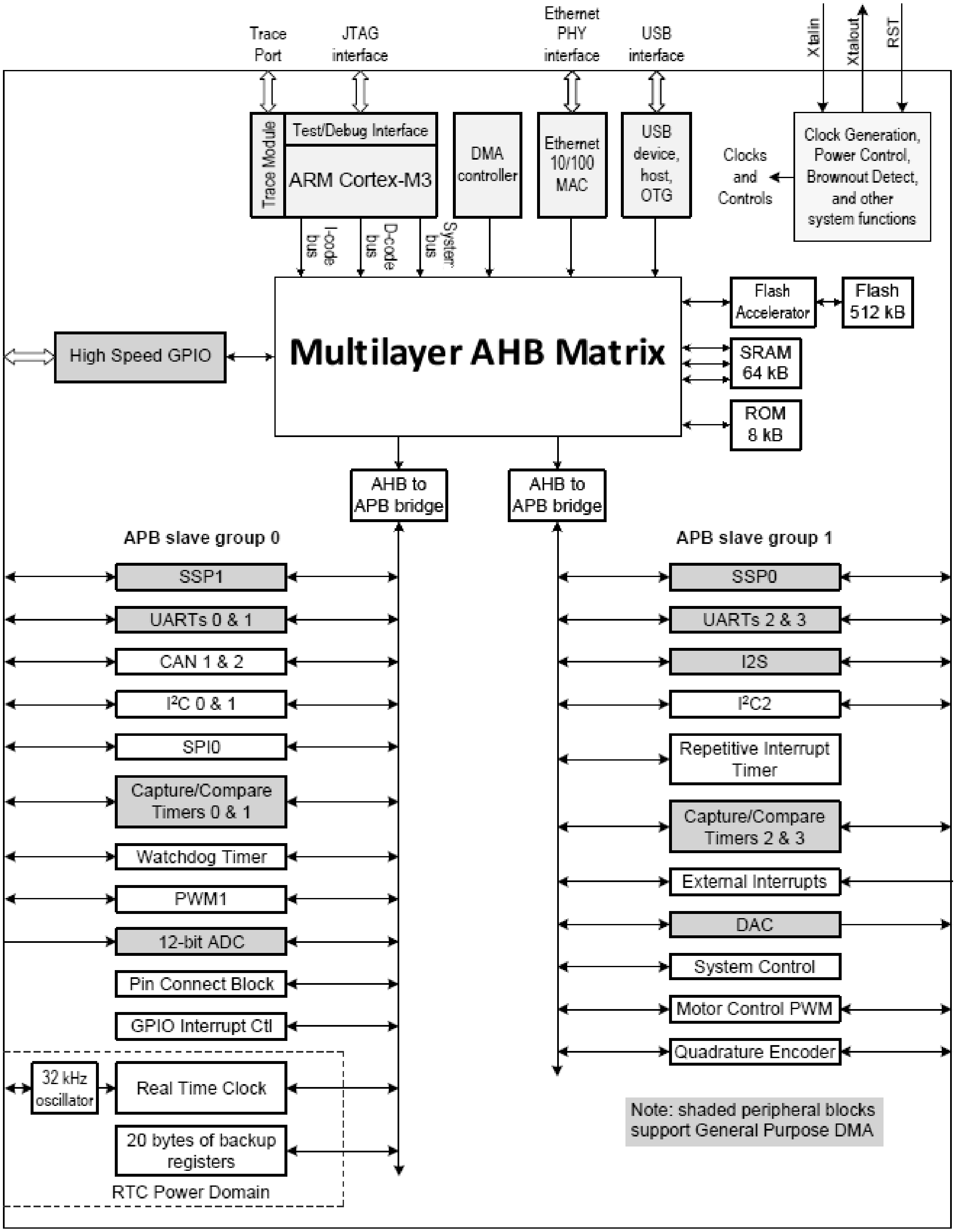


Fig. 2 - LPC1769 microcontroller block diagram [11]

IV. LPC1769 MICROCONTROLLER POTENTIALITY

Whereas the ARM Cortex-M3 core and its associated debugging interface are ARM Ltd. products, all other elements incorporated in the microcontroller are specified by the semiconductor manufacturer. The simplified LPC1769 microcontroller block diagram illustrates Fig. 2.

A. *Internal communication*

Fig. 2 shows that the microcontroller core is interconnected with rest of circuitry via three buses: System bus, data bus (D-code bus) and instruction feed bus (I-code bus).

We can find another two main buses in LPC1769 internal circuitry:

• AHB bus (Advanced High-performance Bus) supports direct high speed communication between the microcontroller core and some selected peripherals. DMA controller, Ethernet MAC and USB are included.

• APB bus (Advanced Peripheral Bus) interconnects the other peripherals of LPC1769 microcontroller. There are two such buses and each of them is managing its own peripheral group. That makes a higher communication speed achievement possible. The AHB bus communication employs a special interface (AHB-to-APB-bridge).

Multilayer AHB Matrix is a circuit which acts as interface among core buses, AHB buses, and it facilitates the communication with APB bus interface. Each high speed peripheral is allocated its own communication channel thanks to that circuit and its communication frequency range is not charged with other peripherals.

DMA channel (Direct Memory Access) is a kind of interface enabling the data transfer either between memories or from a peripheral to memory (and vice versa) without charging the processor during the whole transaction period. The processor acts only as a mediator for transaction opening and termination instead of performing instruction at every data word transfer. LPC1769 microcontroller owns 8 DMA channels for general purpose (GPDMA), but some high speed peripherals have their own (dedicated) channel.

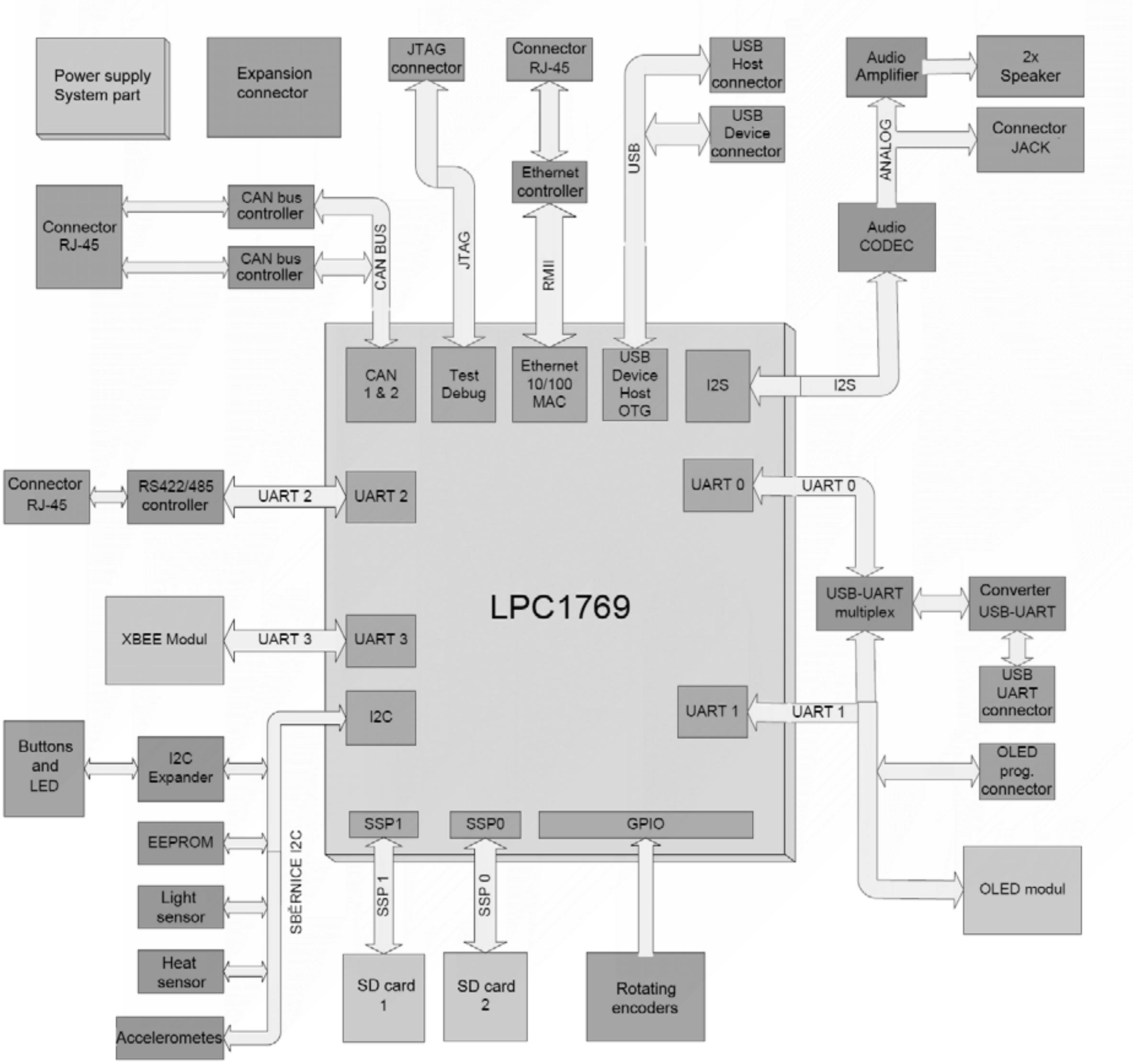


Fig. 3 The CM3board block scheme

B. Memory mapping

LPC1769 microcontroller holds a Flash memory of 512 kB for program storing and a SRAM memory of 64 kB for data storing. The whole processor memory is unified and exploits the common memory space. The addressable space is 4GB in relation to the 32-bit bus (I-code bus and D-code bus). As both buses operate in the same address space, the capacity is not double like it can seem to be.

The individual memory parts have their addresses fixed in the memory space, and it is not possible to change them. The only exception is the interrupt vector table.

C. The interrupt control system

ARM Cortex-M3 core holds a special controller for interrupt control and serving. That controller is indicated with acronym NVIC (Nested Vectored Interrupt Controller).

In case of LPC1769 microcontroller, the NVIC offers following functions:

- 35 peripheral maskable interrupts,
- 32 programmable priority levels,
- the vector table re-mapping possibility,
- non-maskable interrupts support,
- software interrupts support.

Vector table

It is a specific memory area where interrupt vectors are stored. Each vector includes the serving function address for the particular interrupt event. The LPC1769 microcontroller original factory setting positions the table origin at the address 0x00000000 what is the very beginning of the address space. Nevertheless, it is possible to remap that table to another address, either in Flash memory or in SRAM memory. Such remapping is used especially when the address space beginning is occupied by the user boot-loader program. The detailed information on interrupts, their vectors and on table remapping procedures is described in the LPC17xx family user manual [11].

Non-maskable interrupts

This sort of interrupt cannot be generated in a common way. It is frequently generated in cases when the system gets in a intangible state due to a serious error. Non-maskable interrupts have their own servicing functions which can help a designer in a more detailed system diagnostics in case of such error occurrence. A special non-maskable interrupt variant is the system reset.

V. The CM3 development board

The further step was the interfaces and peripheries set for the board. The CM3board block scheme is in Fig. XX.

A. Colour OLED display module

The colour OLED display module with resolution of 320x240, and with integrated intelligent controller, is the product of Australian 4D systems company [5]. That module is an encapsulated unit with entirely autonomous application possibility. The unit consists of OLED panel, intelligent controller, supporting circuits like supply voltage block and uSD card slot. uSD card can serve for storing bitmap files and animation sequences. Display module can communicate with external devices via RX and TX TTL signals similarly like an UART circuit. That communication variant is preferred in the CM3board design, and MCU LPC1769 reserves the UART1 port for it.

This module can operate in two modes. In the first mode, it acts as a serial slave, and it executes commands sent to it. Those commands can comprise for instance, text or bitmap displaying, screen delete, or vector graphics drawing. In the second mode, it acts independently when its controller executes a program written in 4DGL script language [6]. The serial communication here is also possible.

The OLED display module has the resistive touch screen including relevant module for reading and calibration. From a designer point of view, it is possible to work with the touch sensitive surface as with an input device offering two coordinates position.

B. The 24-bit stereo Audio CODEC

The 24-bit stereo Audio CODEC with I2S interface, integrated driver for headphones and 8 to 96 kHz sampling frequency support can exploit many audio functions. It integrates individual components like A/D converter, D/A converter, amplifiers and other supporting circuits. It creates an interface between the digital and analogue device part with bidirectional information flow.

There has been the Texas Instruments TLV320AIC23B integrated circuit chosen for CM3board. That component is marked as IC7 [7]. It is a mixed signal circuit with digital and analogue ground potential separated. The supply voltage is also separated in similar way.

That circuit integrates following functional blocks:

- Two channels sigma-delta D/A converter,
- Two channels sigma-delta A/D converter,
- Power amplifier for headphones direct connection,
- Input circuitry for electret microphone direct connection,
- Digital interface for sound transfer,
- Digital interface for circuit functions control,
- Clock generator and timing circuitry.

AD and DA converters

Those circuits are indispensable for audio interface establishing. The IC7 circuit integrates 4 channels (2 for inputs and 2 for outputs). All channels employ sigma-delta modulation and they function up to sampling frequency of 96 kHz. All converters have resolution of 24 bits.

Headphone amplifier

The headphone amplifier can drive earphone with impedance of either 16 Ohms or 32 Ohms. The headphone amplifier is equipped with volume control, mute mode and it can also suppress interfering audio effects like crackling noise or knocking noise. The amplifier provides up to 40 milliwatt power in each channel for 16 Ohms headphone impedance. The total harmonic distortion (THD) is of 0,1% at 10 milliwat power. [18]

The headphone amplifier output signal on the CM3board is fed to the connector X1 via two separating capacitors C29 and C30 which suppress the DC signal component.

Microphone input

As well as headphone amplifier, the microphone input has the volume control and signal mute mode. The microphone signal is amplified in two stages. The first stage represents an operational amplifier in the MICIN input. That amplifier has the gain adjustable with external resistance in series with this input. The gain without the resistance is set to 5. The second amplifying stage is digitally adjustable and provides the gain either of 0 dB or 20 dB. More information about gain adjustment can be found in the circuit datasheet [18].

The microphone input shares the same AD converter with audio input channel so that it is not possible to use both functions at the same time. However, it is possible to mix the microphone signal with the DA converter signal together.

The microphone is connected to the JP8 connector on the CM3board. The design is but represented with a multi way strip where the biasing voltage for electrets microphone (MICBIAS signal at IC7) and 3.3V supply voltage are lead out besides the microphone input and ground for analogue signal. The supply voltage of 3.3V is filtered with L1, C33 and C34.

Audio digital transmission

The IC7 circuit supports 4 audio digital transmission modes in total. These are as follows:

- Right-justified – bits are aligned to the right within one data word framework
- Left-justified - bits are aligned to the left within one data word framework
- DSP – a special mode for communication with Texas Instruments DSP circuits
- I2S – audio digital transmission bus developed by NXP

These modes are described in more details within the IC7 circuit datasheet [18]. The CM3board is preferably aimed at audio transmission via I2S.

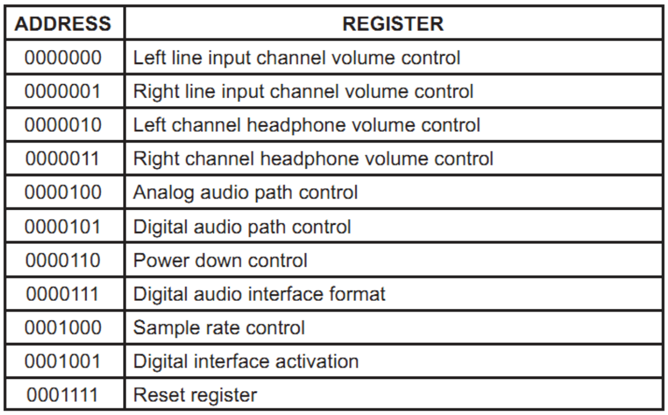
Circuit functions control

The IC7 circuit is controllable with writing in or reading from relevant registers. The communication with those registers can proceed, either via I2C or SPI bus. As both SPI buses on the CM3 board are occupied with high speed communication with SD cards, it was reasonable to use just the I2C bus for the IC7 circuit control. That I2C bus is shared with other circuits using the lower speed communication. Table 1 illustrates the IC7 register map.

Amplifier and acoustic transducers for loud audio replay

The load audio replay mode is supported with two audio transducers and a stereo amplifier embedded in the CN3board. That support is integrated in the IC8 circuit [19]. That circuit has been designed for mobile applications so that the low consumption and high efficiency is preferred. The circuit is formed by two operational amplifiers and it can reach the power of two times 105mW in 16 Ohms loudspeakers and at 5V supply voltage. As the CM3board is fed only with the 3.3V power supply, the maximum loud audio power output is only 40mW for each channel. In spite of that, the power is adequate for informative audio monitoring with SP1 and SP2 loudspeakers.

Table 1 - TLV320AIC23B register map [18]



ADDRESS	REGISTER
0000000	Left line input channel volume control
0000001	Right line input channel volume control
0000010	Left channel headphone volume control
0000011	Right channel headphone volume control
0000100	Analog audio path control
0000101	Digital audio path control
0000110	Power down control
0000111	Digital audio interface format
0001000	Sample rate control
0001001	Digital interface activation
0001111	Reset register

The circuit power supply is separated with the LC filter composed from L3, L4 and C46. The circuit has also an independent analogue ground. Loudspeakers are connected to the output via serial capacitors C48 a C49 which are suppressing the DC signal component. *Loudspeakers* can be disconnected with help of jumpers JP12 and JP13. The circuit can be digitally controlled via three signals which are recognised by MCU as GPIO pins. SPSHTDN signal enables the amplifier switch off while SPCLK and SPUPDN signals serve for a volume control. All these signals are controlled with simple pulses without any special interface.

C. The Ethernet interface with integrated physical layer controller

The LPC1769 does not implement the Ethernet physical layer feature like the native USB. It is implemented with RMII interface here [8]. That interface is a reduced version (using lower count of signal lines) of the MII (Media Independent Interface). That is a device designed exactly for MAC device separation from physical layer (PHY circuit) what causes its complete independency. So it is possible to connect a MCU with a physical layer implemented with any media (metallic cable, optical cable, wireless connection) without any influence on the MCU.

The CM3board implements the Ethernet interface with a standard metallic cable.

D. The RS422/485 communication channel

These interfaces are both implemented with the only integrated IC17. Nevertheless, only one interface mode at time can be operated. That IC17 is ordinarily designed for the RS485 mode and the RS422 mode changes to the point-to-point topology

E. Sensors for non-electrical quantities

Our development kit also supports the non-electric quantities measurement, like illumination intensity, temperature and acceleration.

The temperature sensor represents the IC22 circuit. That circuit measures temperature in the range between -55°C and +125°C. It can act not only as a continuously measurement unit but also a thermostat. If temperature exceeds the set limit, that circuit issues the interrupt signal on the TSINT line. That signal appears at the MCU common input pin so that it cannot cause a real interrupt response. Only in case of necessity, that pin state is to be monitored by software. That signal can be optionally disconnected.

CM3board holds the ambient light sensor IC20 for the display brightness control, and for the push buttons backlight control. Like the temperature sensor, it has an interrupt signal output for a situation when the ambient light exceeds the set limit. That circuit has an internal filter for flickering rejection at frequencies of 50 Hz and 60 Hz what is a frequent problem at artificial light sources. The ambient light is sensed with two integral photodiodes. One of them is sensitive only for the infrared spectrum the other one senses the infrared and visible spectra together. That two-photodiodes combination optimizes the sensor sensitivity close to the human eye characteristics.

Accelerometer detects vibrations, drops, tapping (for example on the display), position change or mechanical shock. The acceleration sensing unit is represented by IC21.

F. Data storing

CM3board contains the 8 kB external EEPROM memory with I2C bus. That memory is represented by IC19 (36) circuit and its address can be jumper adjusted. That memory can store a small data amount like device user configuration, events log, errors log, and/or peripheral device measurement data.

If we need to store larger amount of data, like audio files, image files, long term recorded data, or MCU new firmware files, CM3board offers two slots for either SD card or for X8 and X9 MMC card. These cards are mutually independent and each card communicates via autonomous SPI bus with DMA channel utilization possibility. The slot power supply is separated with LC filters which are connected to MCU via jumpers so that it is possible to disconnect them easily. For case cards are inserted in slots during disconnection, their data lines have pull-up resistors to ensure their logic levels to be defined.

There is no card type support hardware-wise defined. As all MMC, SD, SDHC, and new SDXC cards are hardware-compatible, the particular card support is selectable with software support. The theoretical SDXC memory capacity limit is up to 2 TB.

G. Further important kit components

The list of further important development kit components follows:

- Native USB 2.0 interface with Device, Host, and OTG support
- USB-UART converter with virtual serial port
- Integrated D-class amplifier, and two mini-loudspeakers for loud listening incorporated in the board
- JTAG port for testing and application debugging
- CAN bus interface with two independent channels
- Wireless XBEE module
- Eight user push-buttons with programmable LED backlight and innate I2C bus expander
- Two rotary encoders
- Serial 8 kB I2C EEPROM
- Extension connector for external user hardware connection.

VI. Real Time Operation System

The continuously growing nowadays microprocessors´ capacity is accompanied with growing requirements in application areas. While the last century 70s and 80s processors common programming language was assembler, the nowadays processors are commonly using higher level programming languages. The object programming concept and software platform like .NET and Java represent no exception at nowadays microprocessors.

Not only programming languages are determining the development trends in this specialized area. The increasing demand on real time applications has evoked the formation of application specific operation systems. The RTOS systems have occupied its firm position in the industrial praxis. Unlike common personal computers operation systems, these systems are very specific and their presence in the particular equipment is not necessarily recognizable for the user. We can encounter them almost everywhere from consumer electronics like toys, white goods, PC accessories and network components to industrial automation systems, automotive industry, biomedical engineering or space research.

The current market offers a wide range of such systems for commercial and non-commercial applications. These systems are sometimes accessible without charge like open-source systems. One of them is the FreeRTOS system.

A. Motivation for implementing RTOS

We can always ask the question whether to use RTOS or not. Generally, smaller projects can be managed without it while it can act as a very useful tool for the larger ones where it can bring the higher level of organisation. The boundary between a smaller and a larger project is always questionable and that depends always on the particular situation evaluation related to the architecture, real-time response requirements and similar stumbling blocks.

A CM3board demonstration application is quite simple so that it can do without RTOS. Nevertheless, the tutorial aspect calls for RTOS implementing in the project.

It offers immediately a few advantages for the project:

- Timing abstraction – it is very likely the most useful benefit in this demo application. The timing is not realized with hardware timers or with delay loops, but the API RTOS is used where we can pause some tasks for precisely set time period and we can perform another activities in between.
- Increased modularity – tasks are mostly autonomous software elements which can be treated separately. There are also better possibilities for a team development in case of rigorously defined autonomous task interfaces.
- Easier testing – the above stated implies that it is possible to

test to a certain degree and debug the task in isolation from environment.

- The processor idle time utilization – designer has a much higher control over the processor time in case of multitask system, and he can more precisely make use of it. Processor usually performs activities only in case there are any expected. It may not provide the full performance with endless loops exercising during idle time, but it can switch the whole circuitry in an energy saving mode, or it can optionally perform some activities in the background.

B. *FreeRTOS system potentiality*

FreeRTOS system is almost exclusively written in C language and its source code files can be smoothly embodied in a C++ project. FreeRTOS is circulated under the GPL licence and there is possible to use it free of charge including its source codes. System is adopted on numerous architectures which list you can find on the system official website [22].

C. *Task management*

FreeRTOS system offers a few API functions for task management. They are its basic functions. It is possible to create task with help of xTaskCreate() function and to cancel it with help of xTaskDelete() function. Every task created has to be implemented as an endless loop similarly like the main() function. It is also possible to use task temporarily blocking functions, for instance vTaskDelay(). FreeRTOS system implements always at least one task, so called idle task which has the lowest priority, and which runs always when no other task is in the ready state. The first chapter of reference [12] deals with task management or the information can be found in the manual accessible on the FreeRTOS official website [13].

D. *Queues and inter task communication*

Queues are generally used for communication among tasks. They are autonomous objects encapsulating FIFO sort of buffer in them. As well as tasks, queues have their API which enables queues creation, deleting and also data storing and withdrawal. Queues hold finite number of fixed elements which qualities are specified during the queue formation. Tasks own functions that facilitate the waiting in a blocked state until data comes in the queue, or until a queue free space emptying enables the data [12].

E. *Semaphores and interrupt management*

Semaphores serve also for mutual task communication preferably for their synchronization. We differentiate the binary and counting semaphores. Semaphore can be interpreted as a queue containing only one element in case of binary semaphore, or optionally more elements in case of counting semaphore. Unlike the standard queue, the element content is not important only its presence or absence in the “queue”, more accurately in the semaphore. As well as queues, also semaphores are objects by themselves and FreeRTOS owns API functions for their creation, deleting and controlling. The task synchronization with an interrupt belongs among semaphores frequent applications. The particular interrupt ISR task is the waiting task semaphore set (interrupt handler) for the task with very high priority but blocked by waiting most of time. Immediately when the semaphore is set, that task is launched and exercises the interrupt relevant service [12].

F. *Memory management*

Working with FreeRTOS, it is possible to make use of standard functions for the dynamic memory allocation, i.e. malloc() and free(). These functions are not always suitable because of relatively large implementation and with limited or no accessibility for smaller systems. Another problem can be related to the fact that these functions cause memory fragmentation, and that they are not deterministic. The multitask applications safe use is also not guaranteed. FreeRTOS system implements three ways how to avoid those problems. Each of those ways is implemented with separated file.

G. *Platform ARM Cortex-M3 specific functions*

Majority of Cortex-M3 core microprocessors offer so called MPU (Memory Protection Unit) what is a peripheral facilitating the memory segmentation in autonomous regions where each region is managed independently with its own access rights. The LPC1769 microprocessor by NXP, for instance, enables segmentation in 8 such regions [14].

FreeRTOS system owns functions for cooperation with MPU on the Cortex-M3 platform. It is mainly the function vTaskAllocateMPURegions() which enables to allocate the autonomous region in the memory. With help of vTaskCreateRestricted() function is formed a task then exploiting that memory area. Many others such functions are described in the on-line manual on FreeRTOS system website [15].

VII. Software

There is possible to utilize many development environments for application software design. Each of them has its advantages and disadvantages, like price, user-friendliness, non-standard functions utilization etc.

Among most exploited development environments, we can mention Eclipse with Cygwin GNU ARM Tool-chain [9] or YAGARTO supplements, furthermore Keil, IAR, Red Suite.

That is the Red Suite light version named LPCXpresso which has been used in our project. Although it supports only C programming language, and the program size is limited to 128 kB, it represents a so called download limit what means the program size to be written and developed with the help of debugger. There is no limit for program compilation. This is a free version and it represents an excellent combination with identically named development tools by Embedded Artists company.

The microcontroller operation control is exclusively managed by the user.

There has been created a simple demonstration program for CM3board. The demonstration of multimedia elements is pre-eminently accented in that program. The multimedia demonstration is aimed at the static pictures stored in the touch-sensitive OLED module SD card browsing.

We can summarize the individual steps of demo application design in following items:

- OLED module application design aimed at the graphics loading and displaying including the serial communication with the CM3board.
- Controller design for the PCA9555 circuit embedded in the CM3board.
- Creation of the push-buttons operation library for PCA9555 disposal.
- A simple protocol design for communication between OLED module and CM3board.
- Application layer creation with the help of FreeRTOS system.

Except for the above mentioned items there were also other software elements used for our application:

- FreeRTOS system libraries,
- CMSIS library,
- LPC1769 circuit peripheral controllers.

VIII. The development kit components

The development kit does not comprise only the main board, but it includes many options for applications support as well.

The support option set contains the following items:

- Switching power supply adaptor 9 Volt
- 3Mini USB cables
- User manual and
- CD ROM with development environment demo version and with application examples
- Colour OLED module
- Transportable suit-case

IX. Conclusion

There has been a new 32-bit ARM core microcontroller development kit designed in the frame of our project. A prototype has been manufactured for all required functions verification. The final device has a variety of applications comprising both the student laboratory educational activities and the cheaper control devices development for various automation areas.

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