Microcontrollers

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Architecture, Implementation, & Programming

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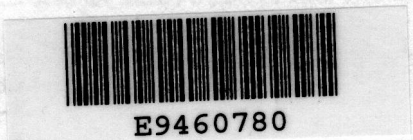

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Readers should test any program on their own systems and compare results with those presented in this book. They should then construct their own test programs to verify that they fully understand the requisite calling conventions and data formats for each of the programs. Then they should test the specific application thoroughly.

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Preface

Microcontrollers are digital computers particularly designed to supervise, manage, monitor, and control various processes in industry, business, defense, aerospace, and other areas of application. With the advent of VLSI technology, microcontrollers are becoming essentially single-chip microcomputers. As the technology advances, microcontroller chips attain higher density, and more and more equivalent transistors can be placed on a single chip—over a million at the beginning of the nineties and over 50 million around 2000, as promised by some chip manufacturers. A microcontroller chip, being a self-sustained microcomputer, contains in addition to a central processing unit (CPU), cache, main memory (more memory is placed on a chip as technology develops), input/output (I/O) interfaces, direct memory access (DMA) controllers, interrupt handlers, timers, and other subsystems necessary to implement an efficient microcontroller.

Microcontrollers, being a particular case of digital computers, have to be programmed so that they can perform their assigned tasks. In the control of relatively simple processes, such as a single traffic intersection, one can probably get by with a relatively short and simple assembly language program. However, many processes are very complicated and require lengthy and sophisticated software. In such cases, assembly language programming is too time-consuming and impractical. Thus, high level language (HLL) programming (such as in C, ADA, or PASCAL) becomes an indispensable necessity. Naturally, one has to develop efficient approaches for generating useful and reliable microcontroller software, be it in assembly, HLL, or a combination of the above.

The goal of this book is to present to the reader a unified document containing a variety of aspects involved in the design and implementation of microcontrollers. The book covers microcontroller architecture, organization, structure, and assembly and HLL (with a stress on the C language) programming. In addition, the text presents a number of examples of actual microcontrollers of different capabilities, currently available on the market. Design examples based on existing commercial microcontrollers are also included.

The book is not intended for beginners in computers. It is assumed that the reader has had a basic course in computer organization and in programming of at least one assembly and one HLL computer programming language. The book can be used as a reference text by practicing engineers, computer scientists, and other professionals involved in the design and implementation of microcontrollers. It can also be used as a textbook in special senior level or first-year graduate courses on microcontrollers. Such a course (ECE 447) is indeed being taught at the authors' school, the George Mason University (GMU). It is a senior course, and a significant part of the material in the text was successfully presented in it. Parts of the book were also taught in other GMU courses, such as a senior course on computer design and a graduate course on advanced microprocessors. Since microcontrollers are applied in practically all industrial areas, the text can be used in any engineering curriculum. It can also be used by computer science students interested in practical applications.

The book is subdivided into two major parts. The first part (Chapters 1 to 4) presents a unified, generic coverage of the principles of microcontrollers, covering their architecture, organization, and software. The second part (Chapters 5 to 7) presents a selection of modern leading microcontrollers, including practical design examples involving some of them. The chapters covering the examples are subdivided according to the basic microcontroller word (or data bus) size: Chapter 5 deals with 4- and 8-bit microcontrollers, Chapter 6 with 16-bit, and Chapter 7 with 32-bit systems. Concluding comments are given in Chapter 8. Although every attempt has been made to include the most current manufacturers data, current detailed design information should be obtained from the individual manufacturers before designing a production microcontroller system.

Some of the examples of actual systems were reviewed by professionals within the particular manufacturing company. The authors would particularly like to thank Mr. Lindsay Wallace of Intel, Mr. Rob Tobias of LSI Logic, Mr. Mike Johnson of AMD (Advanced Micro Devices), Mr. Edward Goldberg of NEC Electronics, Inc., and Mr. Reuven Marko of National Semiconductor for their valuable comments and material made available to the authors. The authors would like to express particular appreciation to Prof. Jack Lipovski (University of Texas, Austin) for reviewing the text for McGraw-Hill and for many helpful suggestions. The authors acknowledge with thanks the editorship of Mr. Daniel Gonneau of McGraw-Hill. This work was partially supported by the Virginia Center for Innovative Technology (CIT) through the Center of Excellence in Command, Control, Communications and Intelligence (C^3I) at George Mason University. Last but not least, the authors would like to express their appreciation to their wives Sue Hintz and Pnina Tabak for their patience and moral support.

Kenneth J. Hintz
Daniel Tabak

Abbreviations

$xxxx:	Hexadecimal number
%xxxx:	Binary number
A/D:	Analog-to-digital
ALU:	Arithmetic logic unit
AMD:	Advanced Micro Devices
BIU:	Bus interface unit
CC:	Condition code
CFG:	Configuration register
CFM:	Control flow machine
CISC:	Complex instruction set computer
CMOS:	Complementary metal oxide silicon
COP:	Computer operating properly, control-oriented processor
CPN:	Colored Petri net
CPU:	Central processing unit
CSG:	Control signal generator
DFM:	Data flow machine
D/A:	Digital-to-analog
DMA:	Direct memory access
DOS:	Disc operating system
DRAM:	Dynamic RAM
DSP:	Digital signal processing
EBCDIC:	Extended Binary Coded Decimal Interchange Code
EBI:	External bus interface
EOC:	End-of-conversion (A/D)
FAM:	Facsimile accelerator module
FAX:	Facsimile
FIFO:	First-in, first-out
FIP:	Fluorescent indicator panel
FIR:	Finite impulse response (filter)
FP:	Frame pointer
FPAL:	Floating-point arithmetic library
FPU:	Floating-point unit
FSR:	Floating-point status register
HCMOS:	High-density CMOS
HLL:	High-level language
HSI:	High-speed input
HSIO:	High-speed I/O
HSO:	High-speed output
Hz:	Hertz, cycles/second
ICE:	In-circuit emulator
ICU:	Interrupt control unit
IMB:	Intermodule bus
I/O:	Input/output
IOP:	I/O processor
IR:	Instruction register
IRQ:	Interrupt request
ISR:	Interrupt service routine
k:	1000
K:	1024
LCD:	Liquid crystal dispaly
LED:	Light emitting diode
LRC:	Local register cache
LRU:	Least recently used
LSB:	Least significant bit
MAR:	Memory address register
MCU:	Microcontroller unit, single-chip microcontroller
MDR:	Memory data register
MIPS:	Microprocessor without interlocked pipeline stages
MMU:	Memory management unit
MODEM:	Modulator/demodulator
MSB:	Most significant bit
N	Petri net with no specific initial marking
(N,M_0):	Petri net with a specific initial marking
NC:	Normally closed (switch)
NMI:	Nonmaskable interrupt
NO:	Normally open (switch)
NRZ:	Nonreturn to zero (signaling)
OEM:	Original equipment manufacturer
Op-code:	Operation code
OS:	Operating system

PC:	Personal computer, program counter (register)
PC:	Programmable controller
PCB:	Process control block
PFP:	Previous frame pointer
PGA:	Pin grid array
PLA:	Programmable logic array
PLL:	Phase-lock loop
PMU:	Peripheral management units
PN:	Petri net
PW:	Pulse width
PWM:	Pulse width modulation
PSR:	Processor status register
PSW:	Program status word
PTS:	Peripheral transaction server
QSM:	Queued serial module
RALU:	Register ALU
RAM:	Random access memory (read/write memory)
RIP:	Return instruction pointer
RISC:	Reduced instruction set computer
ROM:	Read only memory
RPM:	Revolutions per minute
RTOP:	Real time output ports
SA:	Successive approximation (A/D)
SCI:	Serial communications interface
SFR:	Special function register
S/H:	Sample and hold
SIM:	System integration module
SIO:	Serial input/output
SP:	Stack pointer
SPARC:	Scalable processor architecture
SPI:	Serial peripheral interface
SRAM:	Static RAM
TDM:	Time division multiplexing
TLB:	Translation lookaside buffer
TPU:	Time processing unit
UART:	Universal asynchronous receiver transmitter
WSR:	Window select register

Contents

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Chapter

1

Computer, Microprocessor and Microcontroller Architectures

There is a great distinction between computer architecture and organization; the following discussion focuses primarily on computer architecture. *Computer architecture* is a description (definition) of the attributes of a computing system as seen by a machine language programmer or a compiler writer.[1] Writable control stores for modifying microcode during computer operation are not considered available to the normal machine language programmer. *Computer organization* pertains to the various methods that can be used to implement a specific computer architecture. The demarcation between these two components of microcontroller implementation is becoming less distinct with the advent of reconfigurable designs. This will become more evident as this book progresses from the earliest to the most recent designs.

The categorization of computers was once easy because there was a clear difference in cost, amount of memory, type of peripherals, and physical operating speed. While there are still supercomputers, specialized array and pipelined processors, and expensive multiuser computers, the computational capabilities of the most powerful machines of a few years ago have trickled down to the level of personal computers (PCs). An inspection of computer specifications shows that the capabilities of computers in terms of complex arithmetic operations, memory addressing capabilities (virtual address space), as well as amount of connected memory (physical address

TABLE 1.1 MATLAB Benchmarks of Various Computers Showing the Favorable Performance of Microprocessor-Based Machines Relative to Larger Computers

Computer	Figure of Merit Relative to PC/XT @ 4.7 MHZ	KFlop/Second
MAC (8 MHz 68000)	0.2233	3
PC/AT (6 MHz/80286/EGA)	1.3570	15
PC/XT (4.7 MHz/8088/CGA)	1.0000	17
AT&T 6300 (8 MHz/8086)	1.8760	29
Mac II (68020/68881)	6.2358	85
Apollo DN3000 (16 MHz)	5.4287	72
Sun-3/50 (15 MHz with 68881)	5.1628	89
Apollo DN4000 (25 MHz)	9.0300	140
MicroVAX II (VMS/D_floating)	4.1810	140
Mac IIcx (68030/68882)	9.6776	168
803886/80387 (20 MHz, 386-MATLAB)	14.3466	232
Sun-386i (25 MHz)	10.7024	198
VAXStation 3100 (VMS/D_floating)	18.9047	365
Sun-3/260 (25 MHz with FPA)	19.4267	490
Sun-4/110	35.4397	730
Sun SparcStation	65.5196	1196
Ardent Titan	61.6884	3614

space), have inexorably migrated from the larger to the smaller machines. Even PCs that operate in a single-user mode have comparable computational capabilities to those of much larger machines as is shown by the comparison of MATLAB benchmarks in Table 1.1. The seven standard benchmarks that were run are

1. N = 50 real matrix multiply
2. N = 50 real matrix inverse
3. N = 25 real eigenvalues
4. 4096-point complex FFT
5. LINPACK benchmark
6. 1000 iteration FOR loop
7. N = 25 3-D mesh plot

The geometric mean of the execution times was computed to determine a figure of merit relative to a PC/XT machine. Table 1.1 also lists the KFlop/s throughputs of the various machines. Initially microcontrollers were thought to be simpler implementations of computers with a limited instruction set and enhanced I/O capabilities that could be mass-produced inexpensively. With the advent of increasingly complex microcontrollers, including single-chip microcontrollers with complex computational capabilities and 32-bit architectures, microcontrollers have taken on a new set of problems such as digital signal processing, computer peripheral control, and real-time detection and modulation/demodulation of FAX signals as well as complex non-linear control problems. One can no longer look at just simple parameters such as number of instructions, quantity of virtual and physical memories, and processing speed to separate supercomputers from microcontrollers. The functional use of the computer determines whether it is a microcontroller, computer, or supercomputer. It is not too difficult to conceive of a massively parallel computer that uses all of its computational resources to maintain tracks of aircraft and direct the air traffic control (ATC) in a specific geographic area. There is a lot of computation performed in correlating radar returns, merging and splitting tracks, and predicting trajectories of aircraft for collision avoidance and routing. However, the computations are incidental to the primary function of the computer, which is air traffic control. There is, however, a clear distinction on closer inspection, when one studies the capabilities of an instruction set relative to a particular problem. Continuing with this example, if there are included in the instruction set single instruction operations for performing the discrete Fourier transform (DFT) as well as matrix operations, the computations necessary for target tracking can be performed more efficiently. If there are many I/O instructions that can interact directly with the contents of memory, then the computer can be interfaced more easily with radar inputs and control outputs. If there is a complex set of graphical primitive operators, then the computer can more effectively display the information to the human operators. When it comes to control, the application, more than the descriptive title of the computer or integrated circuit, must be used in selecting the correct hardware. However, microcontrollers will be considered to have all of the elements of a computer on a single integrated circuit (IC) and be able to operate with few or no external components.

Control and *microcontrollers* mean different things to different people. The ATC system is an example of control, but so is the control of motors in industrial settings, the control of microwave ovens, the control of videocassette recorders (VCRs), the control of drug administration to hospital patients, the replacement or bypassing of human nervous systems that have been damaged, the control of bank (automatic) teller machines (ATMs), the control of remotely piloted or autonomous vehicles for operations in hazardous environments and the control of automotive engines for

pollution reduction and improved efficiency. It is not possible for one type of controller to meet all of the diverse requirements of these various applications; this prompts the impartial study of the various architectures and organizations of microcontrollers. No single computer or microcontroller is the best for all applications, and only a thorough understanding of the alternative implementations and their impact on design will allow one to select the correct hardware and software configuration for a particular application. This is the source of our egalitarian approach to computers, which implies that there is no hierarchy among computers, only the correct computer as determined by the particular application. There is no hierarchy between software and hardware, only the right application of each capability to solve the task at hand.

1.1 THE ESSENTIAL ELEMENTS OF A COMPUTER

There are five essential elements of a computer: the arithmetic logic unit (ALU), the input section, the output section, the control unit (CU), and the memory. These are shown in the block diagram of Fig. 1.1. The input and output sections are commonly referred to by their collective name of input/output (I/O), and depending on the convenience of the situation, they may be treated collectively or individually. All of these elements are necessary to form a complete computer. If there is no input, the computer cannot respond to its environment. If there is no output, the computer cannot effect changes in its environment. If there is no ALU, the computer cannot perform alterations of its input but only move it from one storage location to another and/or pass it from inputs to outputs. If there is no memory, the system is no more than a finite-state machine. And while most microcontroller applications can be represented by and behave as finite-state machines, computers' memory allows them to realize any finite-state machine as well as compute any computable number. For an expansion of

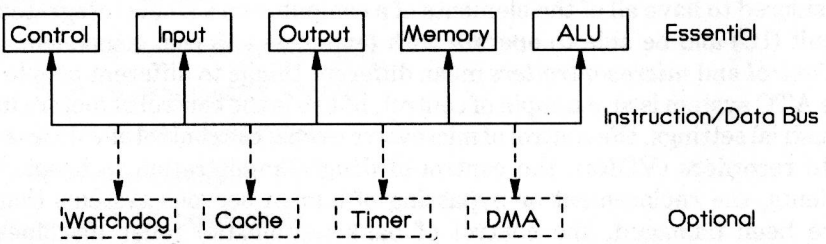

Figure 1.1 Required and typical optional elements of a single-chip computer.

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