program control, sequencing and supervising operations. The general-purpose instruction set is always specific to a specific CPU. Any CPU must possess the following basic functional units:

1. A control unit that fetches and controls the sequential processing of a given command or instruction and communicates with the rest of the system.
2. An ALU that undertakes arithmetic and logical operations on bytes or words. It may be capable of processing 8, 16, 32 or 64-bit words at an instant.

A microprocessor is a single VLSI chip that has a CPU and may also have some other units (e.g., caches, floating point processing arithmetic unit, pipelining and superscaling units) that are additionally present and that result in faster processing of instructions.

The earlier generation microprocessor's fetch-and-execute cycle was guided by a clock frequency of the order of ~4 MHz. Processors now operate at a clock frequency of 4 GHz and even have multiple cores. In early 2002, it became possible to design Gbps (Giga bit per second) transceiver and encryption engines in a few highly sophisticated embedded systems using processors that operate on GHz frequencies. A transceiver is a transmitting cum receiving circuit that has appropriate processing and controls units, for example, for controlling bus-collisions. An encryption engine is a system that encrypts the data to be transmitted on the network.

Intel 80x86 (also referred as x86) processors are the 32-bit successors of 8086. [The *x* here refers to an 8086 extended for 32 bits.] Examples of 32-bit processors in 80x86 series are Intel 80386, 80486 and Pentiums (a new generation of 32- and 64-bit microprocessors is the classic Pentium series). IBM PCs use 80x86 series and the embedded systems incorporated inside the PC for specific tasks (like graphic accelerator, disk controllers, network interface card) use these microprocessors.

High performance processors have pipeline and superscalar architecture, fast ALUs and Floating Point Processing Units (FLPUs). [A pipeline architecture means that the instructions have between 3 and 9 stages. Different instructions are at different stages of the pipeline at any given instance. A superscalar architecture refers to two or more sets of instructions executing in parallel pipelines.]

The important microprocessors used in the embedded systems are ARM, 68HCxxx, 80x86 and SPARC family of microprocessors.

Section 1.7 will describe the embedding of a microprocessor GPP in complex systems.

A microprocessor is used as general-purpose processor when large embedded software has to be located in the external memory chips.

1.2.3 Microcontroller

A microcontroller is an integrated chip that has processor, memory and several other hardware units in it; these form the microcomputer part of the embedded system. Figure 1.2 shows the functional circuits present (in solid boundary boxes) in a microcontroller. It also shows the application-specific units (in dashed boundary boxes) in a specific version of a given microcontroller family.

Just as a microprocessor is the most essential part of a computing system, a microcontroller is the most essential component of a control or communication circuit. A microcontroller is a single-chip VLSI unit (also called 'microcomputer'), which, though having limited computational capabilities, possesses enhanced input–output capabilities and a number of on-chip functional units. [Refer to Section 1.3 for various functional hardware units.] Microcontrollers are particularly suited for use in embedded systems for real-time control applications with on-chip program memory and devices.

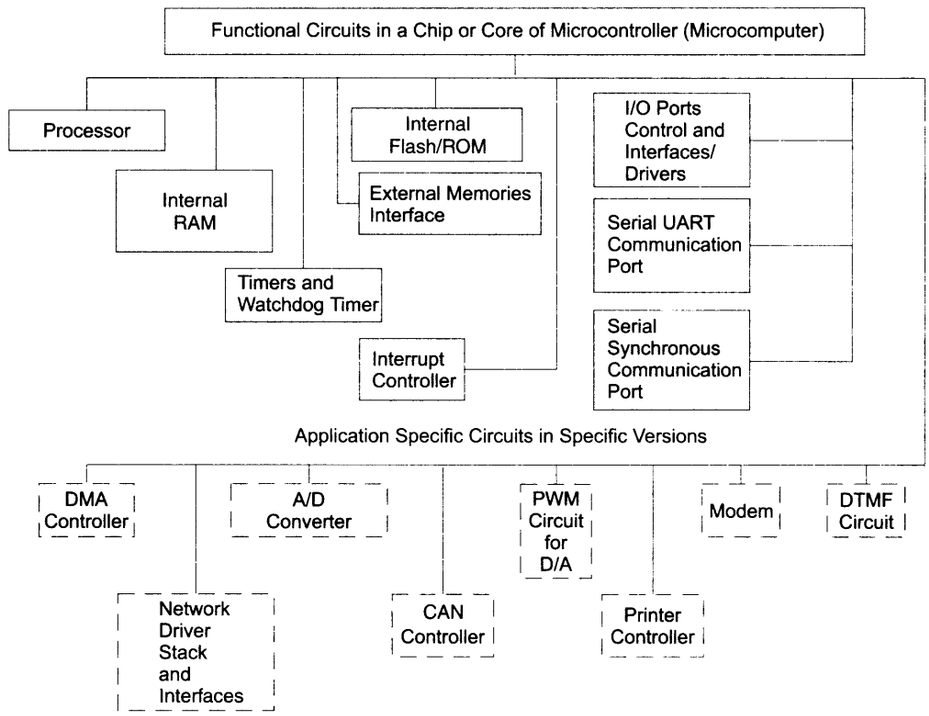

Fig. 1.2 Various functional circuits (solid boundary boxes) in a microcontroller chip or core in an embedded system. Also shown are the application-specific units (dashed boundary boxes) in a specific version of a microcontroller

A few of the latest microcontrollers also have dual core and high computational and superscalar processing capabilities. Important microcontroller chips for embedded systems are 8051, 8051MX, 68HC11xx, HC12xx, HC16xx, PIC 16F84 or 16C76, 16F876 and PIC18, microcontroller enhancements of ARM9/ARM7 from ARM, Intel, Philips, Samsung and ST microelectronics.

Figure 1.3 shows commonly used microcontrollers in small-, medium- and large-scale embedded systems. Choosing a microcontroller as a processing unit depends upon the application-specific features in it.

A microcontroller is used when a small or part of the embedded software has to be located in the internal memory and when on-chip functional units such as the interrupt-handler, port, timer, ADC, PWM and CAN controller are required.

1.2.4 Single Purpose Processors

Single purpose processors used in embedded systems include:

1. Coprocessor (for example, for floating point processing).

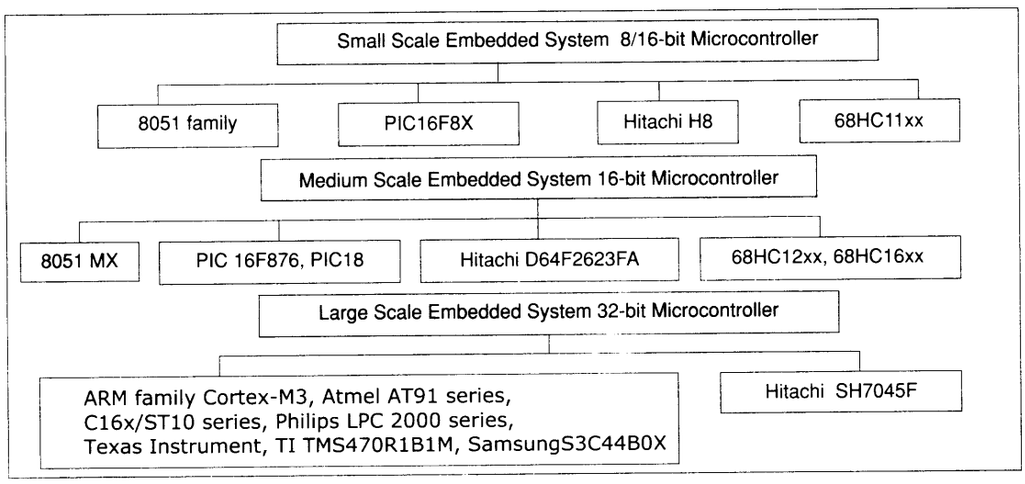

Fig. 1.3 Commonly used microcontrollers in small-, medium- and large-scale embedded systems

2. Graphics processor: An image consists of a number of pixels. For example, Quarter common intermediate format—Quarter-CIF images have 144 × 176 (horizontal x-axis × vertical y-axis) pixels. Video frames have 525 × 625 pixels. The video graphic adapter (VGA) format of e-mailing and web pages has 640 × 480 = 307,200 pixels. A separate graphics processor is required for functions such as, for example, gaming, display from graphics memory buffers and to move (translate on screen) and rotate an image or its segments.
3. Pixel coprocessor: High-resolution pictures have formats: 2592 × 1944 pixels = 5,038,848 pixels; 2592 × 1728 = 3.2 M; 2048 × 1536 = 3 M and 1280 × 960 = 1 M. A pixel coprocessor is required in digital cameras for displaying images directly or after operations such as rotate right, rotate-left, rotate-up, rotate-down, shift to next, shift to previous.
4. Encryption engine: A suitable algorithm runs in this processor to encrypt data for secure transmission.
5. Decryption engine: A suitable algorithm runs in this processor to decrypt the encrypted data at receiver's end.
6. A discrete cosine transformation (DCT) and inverse transformation (DCIT) processor is required in speech and video processing.
7. Protocol stack processor: A protocol stack, which has a number of header words, is prepared before an application data is sent to a network. At the receiver's end, the protocol stack is received and application data is accepted accordingly. A TCP/IP protocol stack processor processes TCP/IP network data.
8. Network processor: A network processor's functions are to establish a connection, finish, send and receive acknowledgements, send and receive retransmission requests and check and correct received data frame errors. The network processor's functions include all protocol stack-processing functions.
9. Accelerator (for example, Java codes accelerator). The accelerator is a coprocessor that accelerates computations by taking advance actions that are just-in-time compilations of the next object in Java programs.
10. CODEC (Coder and Decoder): A CODEC is a processor circuit that encodes input and decodes the encoded information or bits or signals into a complete set of bits or original signal. Voice, speech,

image, video signals and bits are encoded for storing or transmission and decoded from the stored or received bits or signal for display or playing. The CODEC functions as a compression and decompression unit for voice, speech, image or video signals.

11. JPEG CODEC: This is a processor for jpg compression and decompression. The Joint Photographic Experts Group (JPEG) is an International Telecommunication Union for Telecom (ITU-T) and International Standards Organisation (ISO) committee.
12. MPEG CODEC: The Motion Pictures Experts Group (MPEG) recommends CODEC standards for video. MPEG3 CODEC is a processor for mp3 compression and decompression. MPEG 2 or 3 or 4 compression of audio/video data streams is done before storing or transmitting, and decompression is done before retrieving or playing files. For MPEG compression and decompression algorithms, if GPP-embedded software is run, then separate DSPs are required to achieve real-time processing.
13. Controller (e.g., for peripheral, direct memory access or bus).

Single purpose processors are used for specific applications or computations or as controllers for peripherals, direct memory accesses and buses.

1.3 EMBEDDED HARDWARE UNITS AND DEVICES IN A SYSTEM

1.3.1 Power Source

Most systems have a power supply of their own. The Network Interface Card (NIC) and Graphic Accelerator are examples of embedded systems that do not have their own power supply and connect to PC power-supply lines. The supply has a specific operation range or a range of voltages. Various units in an embedded system operate in one of the following four power ranges: 5.0 V $\pm$ 0.25 V, 3.3 V $\pm$ 0.3 V, 2.0 V $\pm$ 0.2 V and 1.5 V $\pm$ 0.2 V. There is generally an inverse relationship between propagation delay in the gates and operational voltage. Therefore, the 5 V system processor and units are used in most high performance systems.

Certain systems do not have a power source of their own: they connect to external power supply or are powered by the use of charge pumps (made up of a circuit of diode and capacitor that accumulate charge from the bus signals through which they connect or network to the host or from wireless radiation).

Low voltage operations

1. In portable or hand-held devices such as a cellular phone [when compared to 5 V, a CMOS 2 V circuit power dissipation reduces by one-sixth, ~ $(2\ V/5\ V)^2$. This also increases the time intervals needed for recharging a battery by a factor of six.].
2. In a system with smaller overall geometry, low voltage system processors and IO circuits generate lesser heat and thus can be packed into a smaller space.

A power supply source or a charge pump is essential in every system.

1.3.2 Clock Oscillator Circuit and Clocking Units

The clock controls the time for executing an instruction. After the power supply, the clock is the basic unit of a system. A processor needs a clock oscillator circuit. The clock controls the various clocking requirements of