

### 1.1.6 Performance in Embedded Computing

When we talk about performance when writing programs for our PC, what do we really mean? Most programmers have a fairly vague notion of performance—they want their program to run “fast enough” and they may be worried about the asymptotic complexity of their program. Most general-purpose programmers use no tools that are designed to help them improve the performance of their programs.

Embedded system designers, in contrast, have a very clear performance goal in mind—their program must meet its ***deadline***. At the heart of embedded computing is ***real-time computing***, which is the science and art of programming to deadlines. The program receives its input data; the deadline is the time at which a computation must be finished. If the program does not produce the required output by the deadline, then the program does not work, even if the output that it eventually produces is functionally correct.

This notion of deadline-driven programming is at once simple and demanding. It is not easy to determine whether a large, complex program running on a sophisticated microprocessor will meet its deadline. We need tools to help us analyze the real-time performance of embedded systems; we also need to adopt programming disciplines and styles that make it possible to analyze these programs.

In order to understand the real-time behavior of an embedded computing system, we have to analyze the system at several different levels of abstraction. As we move through this book, we will work our way up from the lowest layers that describe components of the system up through the highest layers that describe the complete system. Those layers include:

- **CPU:** The CPU clearly influences the behavior of the program, particularly when the CPU is a pipelined processor with a cache.
- **Platform:** The platform includes the bus and I/O devices. The platform components that surround the CPU are responsible for feeding the CPU and can dramatically affect its performance.
- **Program:** Programs are very large and the CPU sees only a small window of the program at a time. We must consider the structure of the entire program to determine its overall behavior.
- **Task:** We generally run several programs simultaneously on a CPU, creating a ***multitasking system***. The tasks interact with each other in ways that have profound implications for performance.
- **Multiprocessor:** Many embedded systems have more than one processor—they may include multiple programmable CPUs as well as accelerators. Once again, the interaction between these processors adds yet more complexity to the analysis of overall system performance.

## 1.2 THE EMBEDDED SYSTEM DESIGN PROCESS

This section provides an overview of the embedded system design process aimed at two objectives. First, it will give us an introduction to the various steps in embedded system design before we delve into them in more detail. Second, it will allow us to consider the design ***methodology*** itself. A design methodology is important for three reasons. First, it allows us to keep a scorecard on a design to ensure that we have done everything we need to do, such as optimizing ***performance*** or performing functional tests. Second, it allows us to develop computer-aided design tools. Developing a single program that takes in a concept for an embedded system and emits a completed design would be a daunting task, but by first breaking the process into manageable steps, we can work on automating (or at least semiautomating) the steps one at a time. Third, a design methodology makes it much easier for members of a design team to communicate. By defining the overall process, team members can more easily understand what they are supposed to do, what they should receive from other team members at certain times, and what they are to hand off when they complete their assigned steps. Since most embedded systems are designed by teams, coordination is perhaps the most important role of a well-defined design methodology.

Figure 1.1 summarizes the major steps in the embedded system design process. In this top-down view, we start with the system ***requirements***. In the next step,

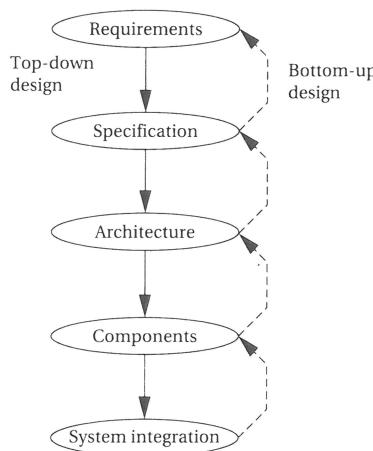


FIGURE 1.1

Major levels of abstraction in the design process.

**specification**, we create a more detailed description of what we want. But the specification states only how the system behaves, not how it is built. The details of the system's internals begin to take shape when we develop the architecture, which gives the system structure in terms of large components. Once we know the components we need, we can design those components, including both software modules and any specialized hardware we need. Based on those components, we can finally build a complete system.

In this section we will consider design from the **top-down**—we will begin with the most abstract description of the system and conclude with concrete details. The alternative is a **bottom-up** view in which we start with components to build a system. Bottom-up design steps are shown in the figure as dashed-line arrows. We need bottom-up design because we do not have perfect insight into how later stages of the design process will turn out. Decisions at one stage of design are based upon estimates of what will happen later: How fast can we make a particular function run? How much memory will we need? How much system bus capacity do we need? If our estimates are inadequate, we may have to backtrack and amend our original decisions to take the new facts into account. In general, the less experience we have with the design of similar systems, the more we will have to rely on bottom-up design information to help us refine the system.

But the steps in the design process are only one axis along which we can view embedded system design. We also need to consider the major goals of the design:

- manufacturing cost;
- performance (both overall speed and deadlines); and
- power consumption.

We must also consider the tasks we need to perform at every step in the design process. At each step in the design, we add detail:

- We must *analyze* the design at each step to determine how we can meet the specifications.
- We must then *refine* the design to add detail.
- And we must verify the design to ensure that it still meets all system goals, such as cost, speed, and so on.

### 1.2.1 Requirements

Clearly, before we design a system, we must know what we are designing. The initial stages of the design process capture this information for use in creating the architecture and components. We generally proceed in two phases: First, we gather an informal description from the customers known as requirements, and we refine the requirements into a specification that contains enough information to begin designing the system architecture.

Separating out requirements analysis and specification is often necessary because of the large gap between what the customers can describe about the system they want and what the architects need to design the system. Consumers of embedded systems are usually not themselves embedded system designers or even product designers. Their understanding of the system is based on how they envision users' interactions with the system. They may have unrealistic expectations as to what can be done within their budgets; and they may also express their desires in a language very different from system architects' jargon. Capturing a consistent set of requirements from the customer and then massaging those requirements into a more formal specification is a structured way to manage the process of translating from the consumer's language to the designer's.

Requirements may be **functional** or **nonfunctional**. We must of course capture the basic functions of the embedded system, but functional description is often not sufficient. Typical nonfunctional requirements include:

- **Performance:** The speed of the system is often a major consideration both for the usability of the system and for its ultimate cost. As we have noted, performance may be a combination of soft performance metrics such as approximate time to perform a user-level function and hard deadlines by which a particular operation must be completed.
- **Cost:** The target cost or purchase price for the system is almost always a consideration. Cost typically has two major components: **manufacturing cost** includes the cost of components and assembly; **nonrecurring engineering (NRE)** costs include the personnel and other costs of designing the system.
- **Physical size and weight:** The physical aspects of the final system can vary greatly depending upon the application. An industrial control system for an assembly line may be designed to fit into a standard-size rack with no strict limitations on weight. A handheld device typically has tight requirements on both size and weight that can ripple through the entire system design.
- **Power consumption:** Power, of course, is important in battery-powered systems and is often important in other applications as well. Power can be specified in the requirements stage in terms of battery life—the customer is unlikely to be able to describe the allowable wattage.

Validating a set of requirements is ultimately a psychological task since it requires understanding both what people want and how they communicate those needs. One good way to refine at least the user interface portion of a system's requirements is to build a **mock-up**. The mock-up may use canned data to simulate functionality in a restricted demonstration, and it may be executed on a PC or a workstation. But it should give the customer a good idea of how the system will be used and how the user can react to it. Physical, nonfunctional models of devices can also give customers a better idea of characteristics such as size and weight.

Name
Purpose
Inputs
Outputs
Functions
Performance
Manufacturing cost
Power
Physical size and weight

**FIGURE 1.2**

Sample requirements form.

Requirements analysis for big systems can be complex and time consuming. However, capturing a relatively small amount of information in a clear, simple format is a good start toward understanding system requirements. To introduce the discipline of requirements analysis as part of system design, we will use a simple requirements methodology.

Figure 1.2 shows a sample **requirements form** that can be filled out at the start of the project. We can use the form as a checklist in considering the basic characteristics of the system. Let's consider the entries in the form:

- **Name:** This is simple but helpful. Giving a name to the project not only simplifies talking about it to other people but can also crystallize the purpose of the machine.
- **Purpose:** This should be a brief one- or two-line description of what the system is supposed to do. If you can't describe the essence of your system in one or two lines, chances are that you don't understand it well enough.
- **Inputs and outputs:** These two entries are more complex than they seem. The inputs and outputs to the system encompass a wealth of detail:
  - **Types of data:** Analog electronic signals? Digital data? Mechanical inputs?
  - **Data characteristics:** Periodically arriving data, such as digital audio samples? Occasional user inputs? How many bits per data element?
  - **Types of I/O devices:** Buttons? Analog/digital converters? Video displays?
- **Functions:** This is a more detailed description of what the system does. A good way to approach this is to work from the inputs to the outputs: When the system receives an input, what does it do? How do user interface inputs affect these functions? How do different functions interact?

■ **Performance:** Many embedded computing systems spend at least some time controlling physical devices or processing data coming from the physical world. In most of these cases, the computations must be performed within a certain time frame. It is essential that the performance requirements be identified early since they must be carefully measured during implementation to ensure that the system works properly.

■ **Manufacturing cost:** This includes primarily the cost of the hardware components. Even if you don't know exactly how much you can afford to spend on system components, you should have some idea of the eventual cost range. Cost has a substantial influence on architecture: A machine that is meant to sell at \$10 most likely has a very different internal structure than a \$100 system.

■ **Power:** Similarly, you may have only a rough idea of how much power the system can consume, but a little information can go a long way. Typically, the most important decision is whether the machine will be battery powered or plugged into the wall. Battery-powered machines must be much more careful about how they spend energy.

■ **Physical size and weight:** You should give some indication of the physical size of the system to help guide certain architectural decisions. A desktop machine has much more flexibility in the components used than, for example, a lapel-mounted voice recorder.

A more thorough requirements analysis for a large system might use a form similar to Figure 1.2 as a summary of the longer requirements document. After an introductory section containing this form, a longer requirements document could include details on each of the items mentioned in the introduction. For example, each individual feature described in the introduction in a single sentence may be described in detail in a section of the specification.

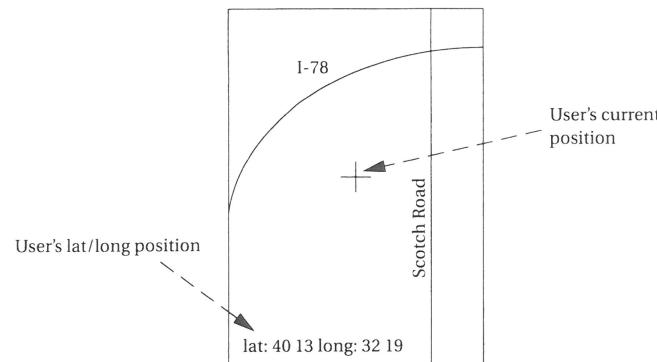
After writing the requirements, you should check them for internal consistency: Did you forget to assign a function to an input or output? Did you consider all the modes in which you want the system to operate? Did you place an unrealistic number of features into a battery-powered, low-cost machine?

To practice the capture of system requirements, Example 1.1 creates the requirements for a GPS moving map system.

### Example 1.1

#### **Requirements analysis of a GPS moving map**

The moving map is a handheld device that displays for the user a map of the terrain around the user's current position; the map display changes as the user and the map device change position. The moving map obtains its position from the GPS, a satellite-based navigation system. The moving map display might look something like the following figure.



What requirements might we have for our GPS moving map? Here is an initial list:

- *Functionality*: This system is designed for highway driving and similar uses, not nautical or aviation uses that require more specialized databases and functions. The system should show major roads and other landmarks available in standard topographic databases.
- *User interface*: The screen should have at least  $400 \times 600$  pixel resolution. The device should be controlled by no more than three buttons. A menu system should pop up on the screen when buttons are pressed to allow the user to make selections to control the system.
- *Performance*: The map should scroll smoothly. Upon power-up, a display should take no more than one second to appear, and the system should be able to verify its position and display the current map within 15 s.
- *Cost*: The selling cost (street price) of the unit should be no more than \$100.
- *Physical size and weight*: The device should fit comfortably in the palm of the hand.
- *Power consumption*: The device should run for at least eight hours on four AA batteries.

Note that many of these requirements are not specified in engineering units—for example, physical size is measured relative to a hand, not in centimeters. Although these requirements must ultimately be translated into something that can be used by the designers, keeping a record of what the customer wants can help to resolve questions about the specification that may crop up later during design.

Based on this discussion, let's write a requirements chart for our moving map system:

Name	GPS moving map
Purpose	Consumer-grade moving map for driving use
Inputs	Power button, two control buttons
Outputs	Back-lit LCD display $400 \times 600$
Functions	Uses 5-receiver GPS system; three user-selectable resolutions; always displays current latitude and longitude
Performance	Updates screen within 0.25 seconds upon movement
Manufacturing cost	\$30
Power	100 mW
Physical size and weight	No more than 2" $\times$ 6, " 12 ounces

This chart adds some requirements in engineering terms that will be of use to the designers. For example, it provides actual dimensions of the device. The manufacturing cost was derived from the selling price by using a simple rule of thumb: The selling price is four to five times the **cost of goods sold** (the total of all the component costs).

### 1.2.2 Specification

The specification is more precise—it serves as the contract between the customer and the architects. As such, the specification must be carefully written so that it accurately reflects the customer's requirements and does so in a way that can be clearly followed during design.

Specification is probably the least familiar phase of this methodology for neophyte designers, but it is essential to creating working systems with a minimum of designer effort. Designers who lack a clear idea of what they want to build when they begin typically make faulty assumptions early in the process that aren't obvious until they have a working system. At that point, the only solution is to take the machine apart, throw away some of it, and start again. Not only does this take a lot of extra time, the resulting system is also very likely to be inelegant, kludgy, and bug-ridden.

The specification should be understandable enough so that someone can verify that it meets system requirements and overall expectations of the customer. It should also be unambiguous enough that designers know what they need to build. Designers can run into several different types of problems caused by unclear specifications. If the behavior of some feature in a particular situation is unclear from the specification, the designer may implement the wrong functionality. If global characteristics of the specification are wrong or incomplete, the overall system architecture derived from the specification may be inadequate to meet the needs of implementation.

A specification of the GPS system would include several components:

- Data received from the GPS satellite constellation.
- Map data.

- User interface.
- Operations that must be performed to satisfy customer requests.
- Background actions required to keep the system running, such as operating the GPS receiver.

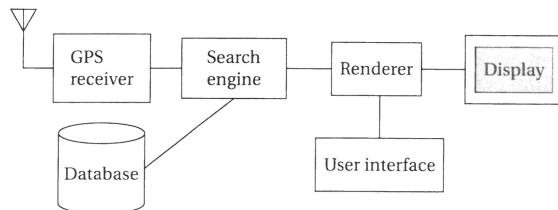
UML, a language for describing specifications, will be introduced in Section 1.3, and we will use it to write a specification in Section 1.4. We will practice writing specifications in each chapter as we work through example system designs. We will also study specification techniques in more detail in Chapter 9.

### 1.2.3 Architecture Design

The specification does not say how the system does things, only what the system does. Describing how the system implements those functions is the purpose of the architecture. The architecture is a plan for the overall structure of the system that will be used later to design the components that make up the architecture. The creation of the architecture is the first phase of what many designers think of as design.

To understand what an architectural description is, let's look at a sample architecture for the moving map of Example 1.1. Figure 1.3 shows a sample system architecture in the form of a **block diagram** that shows major operations and data flows among them.

This block diagram is still quite abstract—we have not yet specified which operations will be performed by software running on a CPU, what will be done by special-purpose hardware, and so on. The diagram does, however, go a long way toward describing how to implement the functions described in the specification. We clearly see, for example, that we need to search the topographic database and to render (i.e., draw) the results for the display. We have chosen to separate those functions so that we can potentially do them in parallel—performing rendering separately from searching the database may help us update the screen more fluidly.

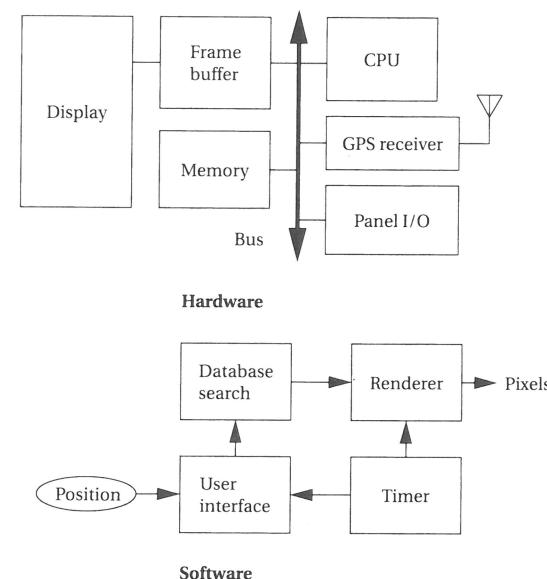


**FIGURE 1.3**

Block diagram for the moving map.

Only after we have designed an initial architecture that is not biased toward too many implementation details should we refine that system block diagram into two block diagrams: one for hardware and another for software. These two more refined block diagrams are shown in Figure 1.4. The hardware block diagram clearly shows that we have one central CPU surrounded by memory and I/O devices. In particular, we have chosen to use two memories: a frame buffer for the pixels to be displayed and a separate program/data memory for general use by the CPU. The software block diagram fairly closely follows the system block diagram, but we have added a timer to control when we read the buttons on the user interface and render data onto the screen. To have a truly complete architectural description, we require more detail, such as where units in the software block diagram will be executed in the hardware block diagram and when operations will be performed in time.

Architectural descriptions must be designed to satisfy both functional and non-functional requirements. Not only must all the required functions be present, but we must meet cost, speed, power, and other nonfunctional constraints. Starting out with a system architecture and refining that to hardware and software architectures



**FIGURE 1.4**

Hardware and software architectures for the moving map.