Chapter 12

Embedded Systems - Design and Development

Things to Look For…

- Things to consider in a design.
- The product life cycle.
- The five steps to design.
- The need to understand the environment and the system being designed.
- The difference between requirements definition and specification.
- Motivation for and objective when partitioning a system.
- Coupling and cohesion and why they are important.
- The differences between functional and architectural models of a system.
- Motivation for and timing of static and dynamic analysis of a design
- Capitalization and reuse of designs.
- Requirements traceability.

12.0 Introduction

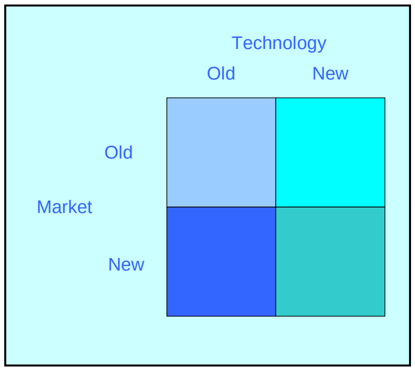
In this chapter, we will study the major phases of the development process for embedded systems. The more detailed aspects of that process will be explored in conjunction with the design and test of the specific hardware and software elements of the system.

In this chapter, we will learn that design is the process of translating customer requirements into a working system and that the complexity of contemporary systems demands a formal approach and formal methods. Working from a formal specification of a problem, we will look at ways of partitioning the system as a prelude to developing a functional design. We will then examine the process of mapping functional model on to an architectural structure and ultimately to a working prototype. To help to ensure the robustness of the ultimate product, we will illustrate how to critically analyze the design both during and after development.

We will also look at several other important considerations in the design lifecycle. These will include intellectual property, component/module reuse, and requirements management and the archival process.

As we begin to think about a new product or adding new features to an existing one, we must look at things from many different points of view. The most important of these is the customer's since he or she finances the development of the product either directly through an agreed upon contract or indirectly through a purchase. The best design of little value if no one is willing to buy. So, we pose the question: What kinds of things should be considered?

If we look at products, we must know how to measure *costs* and *features*. We must be able to identify and distinguish between *real* and *perceived needs*. Too often when we talk with customers about new products, the essential "requirement" in the next generation product is that which was missing when a problem arose this morning.



It's important to learn to make market and technology trade-offs. Several years ago the following very simple table was proposed. Taking *old* technology into and *old* markets is a reasonable and safe strategy. These are the niche markets and often provide support and evolutionary growth for products that are no longer in a vendor's mainstream offering. Taking *new* technology into *new* markets is difficult and risky. At the same time, the rewards can be very high. The personal computer is a very good example. Xerox and Apple both had limited success with their early offerings. The people and the full technology were simply not ready. Taking *new* technology in to an *existing* area or *existing* technology in to a *new* area is easier. At least one portion of the problem - the market or the technology - is well understood and well developed.

We must understand the importance of *deadlines* and *costs*. Product development is based upon a (directly or indirectly) negotiated contract between us and the customer(s). Failure to respect development and delivery costs or schedules leads to loss of sales, market share, and credibility.

We also must always consider *reliability*, *safety*, and *quality* in the products we design. We will study these in great detail shortly. Beyond obvious need to work properly, the product must be *robust*. That is, simply, 'Does it do what it's supposed to?' and 'How does it behave with unexpected inputs?' Robust means much more than this, however. Robust also implies that the system performs even if it is partially damaged, or under extreme temperature conditions, or if it's dropped. If a product does what it's supposed to do but is fragile and buggy, the product is not robust.

The *documentation* we produce to accompany the product must be clear and understandable. The product must be easy to use - intuitive rather than counter-intuitive. *Post sales support,* including the correction of bugs, is very important. Lack of quality has two costs. The first cost is obvious and immediate, the cost to repair, which is often small. The second a hidden cost, the loss of customer confidence and sales, can be very large. Once confidence lost very difficult to regain.

A Simple Example:

Years ago, when developing some of the early microprocessor based embedded systems, we would encounter problems as we debugged the hardware and software. At that time, tools were few and far between. This was a new field.

One very powerful tool for helping to track down such problems is called a logic analyzer. It allows one to follow which instructions the processor is executing (in real-time) and learn why stuff goes in and never comes out. We had to have one, so, our company purchased two of them from two different vendors.

The analyzer from vendor A arrived was out of the box, on the bench, connected to the system, and making useful measurements within 10-15 minutes. Only several days later did anyone think to take a look at the manual. The analyzer from vendor B had a user interface that rivaled a 1040 tax form. Its one-inch thick manual was equally cryptic and demanded several hours of study before even the simplest measurements could be made.

Guess which instrument always has a queue of people waiting to use it and guess which vendor sold us many more instruments.

12.1 System Design and Development

System design and development is a challenging problem. What makes it fun and exciting is that there is a very large creative component to it. There are no rules, no steps to follow to make one creative. There is, however, a large collection of rules to ensure the opposite. Consider a new child. Each comes into this world, eyes wide open with a million questions. Why is the sky blue? Why is the sun yellow? Why can't we see the air? Where does air come from anyway? What do we do? We put them in school. We teach them the rules. Walk into any group of little ones and ask, how many of you can sing? How many of you can draw? Almost every tiny hand leaps up. Go into any similar group of adults and ask the same questions. Everyone is suddenly fascinated with their shoes. One hand may come slowly up. Why? We place too many restrictions on our thinking. Sure, we may need 10 million dollars worth of electronic equipment to give our voice perfect pitch, but, so what. We need to remove artificial restrictions that we impose on our thinking.

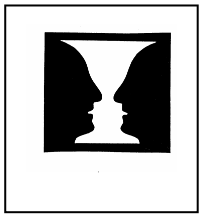
Look at the little ones drawing or coloring. What do we tell them? No, people aren't purple. Cows can't fly. Fish don't have legs - anymore. Oh, and by the way, always color in the lines….and let's also learn how to be creative.

12.1.1 Getting Ready – Start Thinking

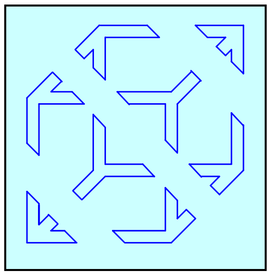
Ok, let's start. Driving is always a good place to begin. The rules are easy. Keep the yellow line on your left and the white on your right – except in Britain and several other places. Now the chance to be creative. In the autumn in the northern parts of the world, the days are warm, but, the nights start getting colder. Often there is a bit of fog that makes an appearance as well. By the morning, the fog and chill have combined to give a very fine glaze of ice on the road. We call this black ice; it gives us the opportunity to be creative. Hop in the car and race out onto the road. What's this nonsense about staying in the lines?

Now perhaps we've decided that maybe we can be just a little creative, let's begin to explore. As we begin thinking about a new design, we'll discover that there are a lot of things to be considered. The problem may not always be what it seems at first blush. Roger van Oech in *A Whack on the Side of the Head*, Warner Brooks, says "Always look for the second right answer." He's right. As we begin, it's important to understand the problem to make sure that we are solving the right problem. Consider the adjacent figure. Which one is the correct image? Is it the old lady or the young one?

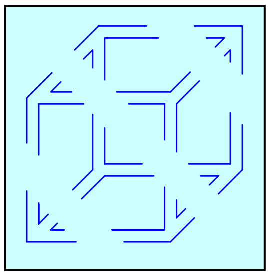
When we begin trying to solve a problem, it's important to talk with everyone involved; to listen to different opinions; to see how the design might affect the people who have to work with it. We have to take the time to look at different views of the problem; to look at it from both the inside and the outside. Based upon our view, we can have a couple of different interpretations of the following problem. Are we building a goblet or are we building two statues?



There will always be occasions in which we have too much information, too many opinions, or too many details. Remember the old expression of not being able to see the forest for the trees. The same holds true as we begin trying to understand a problem during the early stages of a design. Look at this next drawing. What do you see? An interesting design; it looks perhaps like a snowflake. This is a case in which we have too much information.



Let's remove some of the information – if we take a more abstract view of the problem, the solution is easier to see.



Now that we have a start, let's look at the design problem. Let's look at each design as a chance to explore.

12.1.2 Getting Started

Designing and developing embedded systems does raise some interesting challenges and does require a large number of decisions. Some of those decisions require knowledge about the problem, others about the tools and techniques that may be available, and still others choose methods for approaching the solution. There will often be still more things to think about that are not related to the technical part of the problem at all. The collection of these things that we do as we move from requirement to application is often called the *product life cycle*.

Like so many other things in life, there are probably as many different product life cycle models as there are people designing these systems. Who said there isn't any creativity? Each of these models has its supporters and each also has it group of detractors. The goal in the next few pages is to introduce some of the more important things that one should think about when executing a design, present several of the more common life cycle models, and to present some guidelines for things that have worked on successful projects. Despite what they tell you, there are no hard and fast rules. Oops, I lied. There are three: learn a lot with each project, have fun, and do the job right…to the best of your ability. Let's get started.

12.2 Life Cycle Models

The product life cycle of an embedded application is purely a descriptive representation. It breaks the development process into a series of interrelated activities. Each activity plays a role of transforming its input (specification) into an output (a selected solution). The organization of the steps is done according to a *design process model – the life cycle model*. Formality in design provides the structure for a development that lets one creatively explore the design while using the tools to manage some of the more mechanical issues. We use the structure as an aid rather than something that encumbers design.

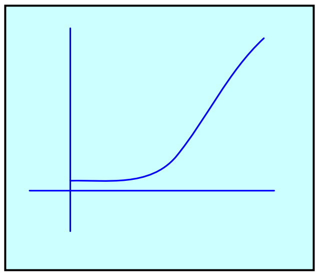
As we've commented already, in the related literature, one can find that a variety of different approaches and models have been suggested. At the end of the day, all have the same basic goal; they all have similar phases. Perhaps, we could more accurately say that they all have similar needs or goals or objectives. These needs are very simple,

- Find out what the customer wants
- Think of a way to give them what they want
- Prove what you've done by building and testing it
- Build a lot of them to prove that it wasn't an accident
- Use the product to solve the customer's problem

Several of the historically more common models or approaches include,

- Waterfall
- V Cycle
- Spiral
- Rapid Prototype

Today, we are continually developing new ones. Which ever model one chooses, the most important point is to understand the meaning and intent or objective of each of the phases or steps in the process. Understand the deliverables for each step as well as the necessary outputs and inputs that are required to move, conclude, or to enter each phase in the selected model. Then follow those – don't take shortcuts. We'll look briefly at each of these four models momentarily. Before we do so, let's look at another model that fits just about any phase of engineering; it looks something like that in the accompanying figure.

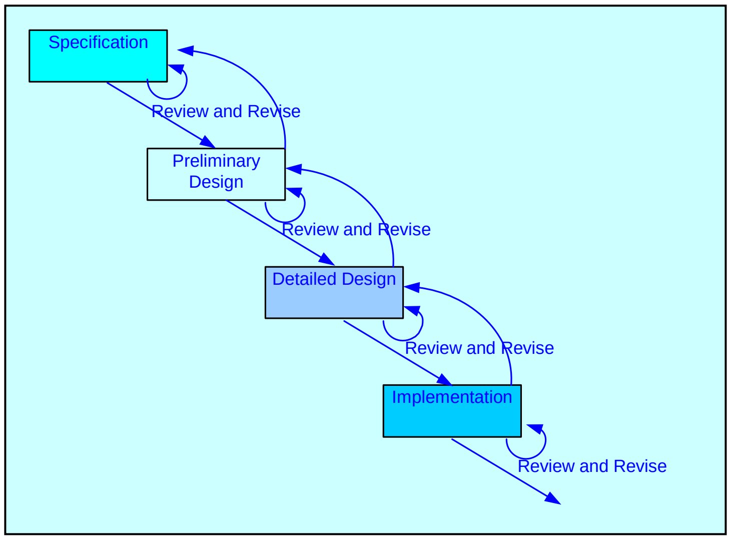


This is called the *hockey stick model* or curve; its shape is strongly suggestive of where the name came from. We've talked about how important it is to address reliability and safety early in the requirements specification and design phases of the life cycle. The hockey stick curve provides an intuitive feel as to why. If we label the horizontal axis as time and the vertical one as cost, and apply it here, we see that the longer we delay in addressing those issues, the greater the cost will be. Cost is not constrqained to be money alone.

Let's begin with the *Waterfall* model. Use your artistic creativity here. Its name evokes its sound which evokes the philosophy and approach engendered in the model.

12.2.1 The Waterfall Model

The *Waterfall model* represents a cycle; a series of steps appearing much like a waterfall, sequentially, one below the next as we see in the following figure.



The steps are given as,

- Specification
- Preliminary Design
- Design review
- Detailed Design
- Design review
- Implementation
- Review

Together, these capture each of the needs that we identified earlier. Successive steps are linked in a chained manner. Such a linking tends to say: *Complete this phase and go on to the next*.

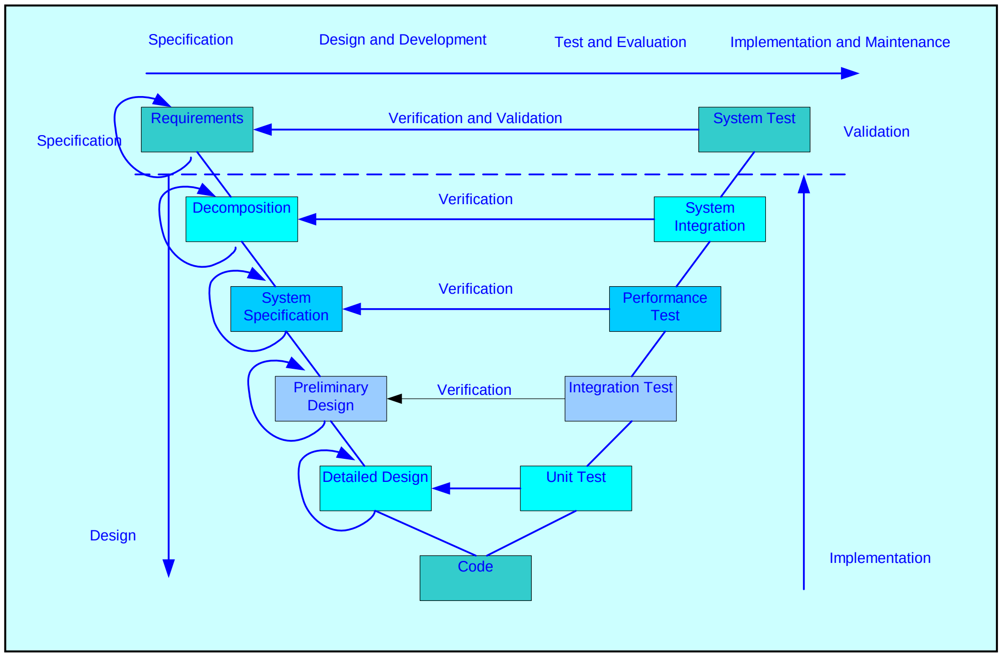
Observe that each phase is also connected back to the previous phase. That reverse connection provides an essential verification link backwards to ensure that the solution (in its current form) agrees with and follows from the specification. With the Waterfall model, the recognition of problems can be delayed until later states of development where the cost of repair is higher (the hockey stick curve). The Waterfall model is limited in the sense that it does not consider the typically iterative nature of real world design.

12.2.2 The V Cycle Model

The *V Cycle* is similar to the Waterfall model except that it places greater emphasizes on the importance of addressing testing activities up front instead of later in the life cycle. Each stage associates the development activity for that phase with a test or validation at the same level. Each test phase is identified with its matching development phase as we see in the following figure.

In the diagram, we have

- Requirements ↔ System/Functional Testing
- High-Level Design ↔ Integration Testing
- Detailed Design ↔ Unit Testing

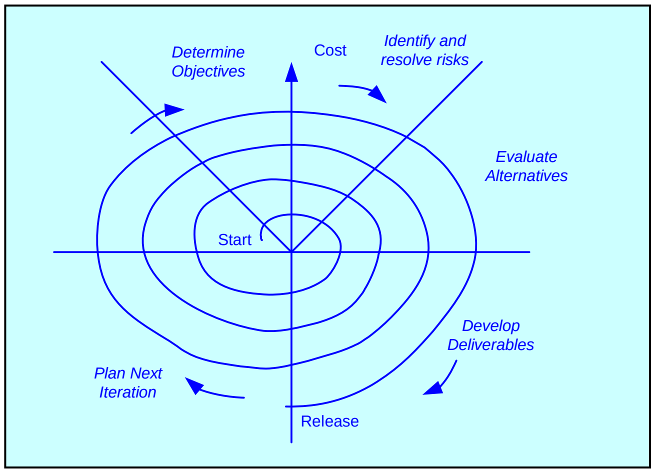


We identify the major phases of a project life cycle across the top of the drawing. These extend from specification to customer delivery and post delivery support. If one follows the sequence down the left hand side of the drawing, one can see that the specification and design procedure utilizes a top down model whereas implementation and test proceed from a bottom up model as is reflected on the right hand side of the drawing.

It's evident that each development activity builds a more detailed model of the system and that each verification step tests a more complete implementation of the system against the requirements at that phase. The development concludes the design and design related test portion of the development cycle of the system with both a verification and a validation test against the original specification.

12.2.3 The Spiral Model

The *Spiral model* was proposed and developed by Barry Boehm, *A Spiral Model of Software Development and Enhancement,* Computer, May 1988. A simplified version of that model is presented in the following figure,



The model takes a risk-oriented view of the development life cycle. Each spiral addresses the major risks that have been identified. After all the risks have been addressed, the spiral model terminates as did the Waterfall and V models, in the release of a product.

Like the earlier models, the Spiral model begins with good specification of the requirements. It then iteratively completes a little of each phase. Its philosophy is to start small, explore the risks, develop a plan to deal with the risks, and commit to an approach for the next iteration. The cycle continues until the product is complete. Boehm's model contains a lot more detail that the one presented here. In both cases, each iteration of the spiral involves six steps,

- Determine objectives, alternatives, and constraints
- Identify and resolve risks
- Evaluate alternatives
- Develop deliverables-verify they are correct
- Plan the next iteration
- Commit to an approach for next iteration

The Spiral model is an improvement on the Waterfall and V models because it provides for multiple builds as well as several opportunities for risk assessment and for customer involvement. However it is elaborate, difficult to manage, and does not keep all developers occupied during all of the phases.

12.2.4 Rapid Prototyping - Incremental

The *Rapid Prototyping model* is intended to provide a rapid implementation (hence the name) of high level portions of both the software and the hardware early in the project. The approach allows developers to construct working portions of the hardware and software in incremental stages. Each stage consists of design, code and unit test, integration test, and delivery. At each stage through the cycle, one incorporates a little more of the intended functionality.

The prototype is useful for both the designers and for the customer. For the designer, it enables the early development of major pieces of the intended functionality of system. By doing so, it helps to establish and verify the structural architecture as well as the control flow through the system. Such an approach permits one to identify major problems early (the hockey stick curve again).

The customer benefits by having the opportunity to work with a functional unit much earlier in the development cycle than with any of the three previous models. The customer can use the prototype in the intended context to provide feedback to the designers about any problems with the design.

Such feedback is a critical aspect of the approach because it encourages backwards or reverse flow through the process. It can be used to refine or change the prototype to correct the identified problems and to ensure that the design meets the real needs of the customer.

The prototype can be either *evolutionary* or *throw away*. It has the advantage of having a working system early in the development process. As noted, problems can be identified earlier and it provides tangible measures of progress. To be effective, however, the rapid prototyping approach requires careful planning both at both the project management level and the designer's level.

Be careful how the prototype is used,

Caution,

The prototypes should never turn into a final product.

Let's now move into the design process. Design begins with the real world. We're trying to solve problems. We're doing so to make our life easier.

12.3 Problem Solving

When we begin the design of a new product or have to incorporate several new features or capabilities into an existing one, we begin with a set of requirements usually stated in text form. The goal is to map those requirements - the real world - through a series of transformations into a solution - the abstract world. During the design process, we move from the concrete, real world into the abstract. These steps comprise what we describe as good design engineering practices.

12.3.1 Five Steps to Design

Hopefully we learned years ago that the first step to design is not to grab the nearest keyboard or processor and start hacking out code or wiring parts together. With today's complex systems, planning and thought before starting are essential to any successful design. If one takes the central elements from each of the life cycle models, one finds that good system designers and successful projects generally proceed using a minimum of five steps. These steps are identified in the following table.

- Requirements Definition
- System Specification
- Functional Design
- Architectural Design
- Prototyping

The formality of each step depends upon the complexity of the end product. If one is working alone or with several others in your own company on a smaller project, a white board in the center of the garage can often suffice. If one is orchestrating a project that includes developers, manufacturers, and regulations in several countries around the world, (which is becoming increasingly common today) the need for formality increases. When working with each of these phases of a product life cycle, one must remember that they are guidelines; collective best practices. They are not a checklist to a successful project; and they are not exhaustive.

Today the contemporary design process must also enforce *IP (intellectual property)*, capitalization and reuse at every design stage. The days of Bob Widler (the father of the op amp) lecturing about integrated circuit design in the bars of Silicon Valley are long gone. One must also consider traceability in both the forward and reverse directions. Traceability captures the relationships between requirements and all subsequent design data and helps in managing requirements changes.

12.4 The Design Process

As we begin to explore the product development cycle, we will walk through each of these five steps. Rather than focus on how one particular model approaches the interpretation of these steps, we will try to identify the essential elements of each step. The approach that we will present is top down and iterative.

The first two steps focus on capturing and formalizing the external behavior of the system. The remaining three move inside the system and repeat the process for the internal implementation that gives rise to the desired and specified behavior. As we will do from the outside, on the inside, we will move from the general to the specific, capturing and specifying the each aspect of the design.

A major task, once we move inside the system, will be that of decomposing and refining the design from a nebulous entity that someone needs into the product that implements that need. We will first decompose (organize) the collection of customer's wishes into functional blocks that are then mapped into an architecture. That architecture provides the aggregate of hardware and software modules that will make up the ultimate system. The final step in the design cycle is that of bringing the design together into a prototype and ultimately into production.

Because there is not one right answer, the problem represents a challenge and an opportunity to be creative. A colleague who worked on numerous designs of a particular piece of measurement technology once said, 'although each design performs exactly the same function, each also represents an opportunity to explore a new approach that is better than the old.' That colleague built a career around doing what everyone else said couldn't be done…including some of the top names in the industry.

One of the best ways to learn how to do something it is simply to do it. So, let's get started. As we walk through each of the steps in the design process that we've identified, we'll see how they apply to the following design. We begin with a textual description.

As a senior development engineer at *Your Time is Our Frequency, Ltd.com*. You've just finished one project and are now getting ready to head off to the next. As part of the early planning of that project, you and one of the marketing folks are traveling around the country talking with people from a number of different engineering firms. You are trying to determine what features your customers would like to see in the next generation product.

You've been on the road with this guy for a couple of weeks now and are anxious to get home. All the cities are beginning to look exactly alike. Tuesday, this must be Cleveland…hmmm, looks just like the last three cities, oh well. This is the last customer for this trip. This morning, you're talking with *High Flying Avionics, Inc*. They're interested in a new counter that can be used on several of their avionics production lines.

Following several hours of discussion with one of the manufacturing managers, you identify most of their requirements. Your discussion with them follows.

Business is a little slow right now and money is tight, so we don't have a large budget to purchase a lot of different new instruments. In fact, ideally, we'd like to be able to use the same instrument on several of our lines.

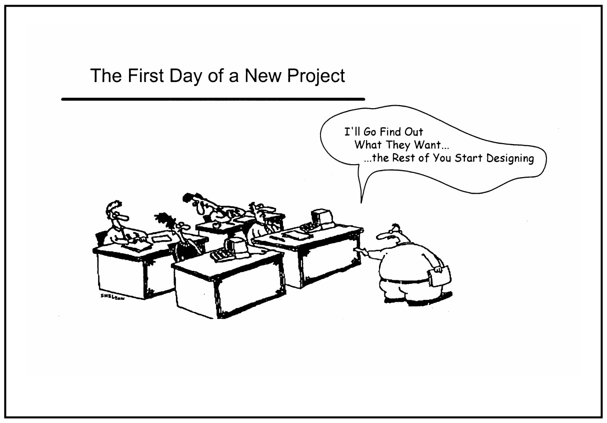
Today, we have our technicians running most of the tests manually, but, in future, we'd like to be able to automate as many of these tests as we can. As we upgrade our systems, we'd like to be able to operate several of these counters remotely from a single PC. Here are some of the other things that we'd like to be able to do.

As part of our ongoing efforts to improve production and flow through our lines, we monitor the rate at which units arrive into each of the major assembly areas. To do that, we need to be able to track how many of our navigation radios come down a production line each hour. Because we support small quantity builds of different kinds of radios, the rate at which the units come past the monitoring points is not constant. As each radio arrives at an entry point, it breaks an IR beam. On most of the lines, breaking the beam generates a 1 μsec wide, negative going 5.0 V pulse. However, we do have several older lines that we must still support. On these, the pulse is positive going.

On several of the newer lines, we have to measure frequency up to 150.000 MHz. We also have several tests for which we must measure frequencies in the range of 50KHz ± 0.001 KHz and 100 Hz with 0.001 Hz resolution. On another line, we have several instruments with output signals that have a duration up to 1.0000 ± 0.0001ms and others that have a duration of up to 9.999 to 10.000 ms and up to 1.000 ± 0.001sec. These signals are not periodic. Finally, we have several periodic signals on those same units that we must be able to measure with the same accuracy and resolution.

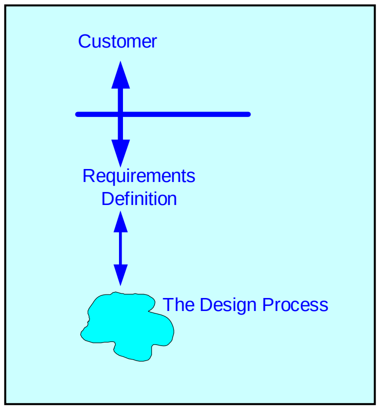
12.5 Identifying the Requirements

The development of any kind of well conceived and well designed system must begin with a requirements definition. Such a need holds, independent of the life cycle model that one chooses to work with. Unlike the people in the accompanying drawing paraphrased from an unknown author, we cannot begin a design until we know what we are supposed to be designing.


The First Day of a New Project
I'll Go Find Out What They Want... ...the Rest of You Start Designing

The goal of the requirements identification process is to capture a formal description of the complete system from the customer's point of view then to document these needs as written definitions and descriptions. Such documentation forms the subsequent basis for the formal design specification.

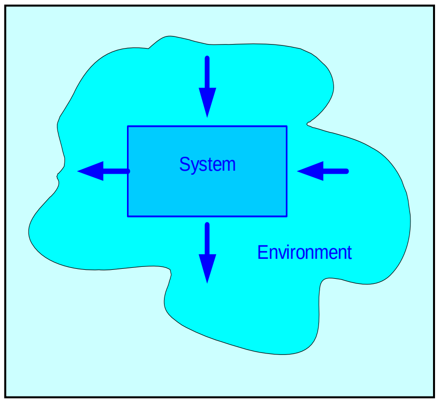
Very often, we use the natural language of the customer and of the application context. We do so because such a formal expression of the requirements forces the early discussion and resolution of many complex problems, involving a variety of people with expertise in many different areas; particularly those who are knowledgeable in the application domain. We express the role that the requirements definition plays between the customer and those who execute the design with the accompanying simple graphic.



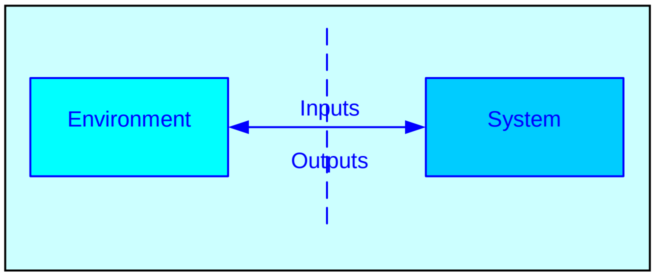
The requirements definition provides the interface between the customer and the engineering process. It is the first step in transforming the customer's wishes into the final product. One can see, then, that the requirements definition is a description of something that is wanted or needed. It identifies and captures a set of required capabilities or operations. As one begins to identify all the requirements, it's important to consider *both* the system to be designed *and* the environment in which it is to operate.

At this early stage in the product life cycle, the goal is to capture and express purely external views of the environment, the system, and their interaction. With respect to the system, one refers to such a view as its public interface. One tries to identify *what* needs to be done (and *how well* it needs to be done) starting with the user's needs and requirements.

The first view of the environment and of the system takes the following form. It's evident that the environment surrounds the system. The inputs to and outputs from the system can come from or go to anywhere in the environment. As one begins, one should make no assumptions about the extent of either.



The first step is to abstract and consolidate that view such that both appear as the black boxes seen below.



The initial focus must be on the world or environment (the application context) in which the system is to operate. Next, one follows with an increasingly detailed description of the role played by the system in that environment and at each step adds to and refines the requirements.

From the perspective of the environment, one can see that the requirements definition must include a specification for the containing environment, a description / definition of the inputs and outputs to and from that environment, a description of necessary behavior of the system, and a description of how the system is to be used.

From the system's point of view, one starts at a high level of abstraction with an *outside* view. One develops the definition(s) that are appropriate for that level. As was done when specifying the environment, through progressive refinement, one moves to lower levels of abstraction and a more detailed understanding and definition.

At this stage in the development life cycle, as the definition of the requirements solidifies and is ultimately formalized into a specification, one should be unencumbered by plans for implementation. The focus should be on the high level behavior of system. The complete, accurate, and internally consistent specification must be available before one can start formal design. Ideally it should be executable and thereby able to work in conjunction with a modeling tool suite. Such an executable specification ultimately serves as basis for validation of the system.

While an executable specification is a laudable goal, difficulties in achieving that goal can occur when one must include support for non-functional constraints, integrate legacy components into an abstract model, and potentially need to be able to combine different domain specific languages and semantics.

12.6 Formulating the Requirements Specification

Let’s now examine some of the things that one should think about when starting to identify and capture the requirements then trying to define them in a formal specification. The form, extent, and formality of such a specification depends upon the project on which one is working, the target audience, and the company for which one is working. Remember, too, that it is a product that is being delivered, not a pile of paper. As a rule of thumb, the specification should be the absolute minimum necessary to capture and clearly identify all of the necessary requirements.

In capturing requirements, one strives to be very specific about the details from the user’s point of view. Bear in mind that one is identifying and formalizing the *requirements*. One still cannot begin to design until the *specification* has been completed and the customer has agreed to it. Remember, too, one should not be discussing microprocessors, memory, peripheral chips, or software modules at this point in the development process.

As one begins the designs, one usually has some general ideas, casual discussion, thoughts, but nothing firm. One can use these as a guide in directing the steps, but one can’t design from them. It’s important to be careful, however, not to rely too heavily on preconceived ideas. One should always be open to alternative approaches. Starting to code or draw logic diagrams at this point is inviting major problems as the project proceeds. In all likelihood, the project will fail.

For the environment, one must establish a description of all relevant entities and of the behaviors of all activities. One must know how the environment is interacting with the system and the effects on the environment by the outputs from the system. For the system, one requires a description of all inputs and outputs as well as a complete description of the functional and operational behaviors and technological constraints.

One can naturally ask at this juncture, how can one get such information about (let alone model) the system and the environment without describing or knowing implementation of the system? The internals are inherently unknown at this point. How does one capture the desired behaviors?

12.6.1 The Environment

A reasonable first step begins with defining and describing the environment; the world in which the system must operate. The environment is a temporal world; it is a heterogeneous collection of entities of one form or another. It comprises the collection of physical devices to which the system is interconnected as well as any physical world attributes that the system is intending to measure or control or that can have an affect on the system. The initial goals in understanding the environment are to identify all relevant entities then characterize their affects on the system and vice versa. When the requirements specification has been completed, one should have all the necessary information about such entities with sufficient detail to support solving the problem.

12.6.1.1 Characterizing External Entities

Each of the entities that make up the environment is characterized by a name and an abstracted public interface. That interface consists of the entity's inputs and outputs as well as its functional behavior. The specification of the external environment should contain the following for each entity,

- *Name and description of the entity*

  The name should be suggestive of what the entity is or does. The description should present the nature of the entity. Is it data, an event, a state variable, a message etc.?

  As an example, an entity may be something that is to be controlled such as the rudder on an aircraft or the clear air turbulence that must be accounted for in such a control system.

- *Responsibilities – Activities*

  What are the activities or actions the environment expected to perform. The hydraulic system moving the rudder is part of the environment. Its action or responsibility is to move the rudder in response to the signal coming from the system being designed.

- *Relationships*

What are the relationships between the entity and its responsibilities or activities? Is that relationship causal or responding? Is it a producer or a consumer?

- *Safety and Reliability*

  Safety and reliability issues must be included early in the specification process. With respect to the environment, at the requirements stage, the focus is primarily on safety. The goal is to identify all safety critical issues and hazards so that they can be addressed in detail in the system design specification. One should also identify any regulatory agencies under whose auspices the system will operate.

12.6.2 The System

Next, focus shifts to the system's point of view. The same questions posed for the environment are now asked about the system. As with the characterization of the environment, the initial goals are to identify all of the aspects of the public interface of the system then characterize their affects on the environment and vice versa.

12.6.2.1 Characterizing the System

Characterization of system begins with the identification of inputs and outputs.

- ***System Inputs and Outputs***
  The system interacts with real world through the entities described and defined in the environmental characterization. The inputs to the system are the outputs from environmental entities and the outputs from the system are the inputs to the environmental entities. One can easily see that the system I/O has already been characterized in environmental entity specification

  For each such I/O variable the following information is already available,

  - ✓ The Name of the signal
  - ✓ The use of the signal as an input or output
  - ✓ The nature of the signal as an event, data, state variable, etc.

Working with the environment specification, one can write the structure, domain of validity, and physical characteristics of each signal. To these, one can add any technical or technological constraints that are identified.

- *Responsibilities – Activities*

  As was done with the specification of the environment, focus now turns to the function that the system is intended to perform. Before it's designed, the system appears as a black box. It can only be viewed from external point of view. A section on functional behavior is now included in the specification.

  The functional description defines the external behavior of the system. It gives a characterization of the affects of the system outputs on the environmental entities and the system's intended response to inputs from the environmental entities. It elaborates how the system is used and to be used by user. Such a specification is equivalent to developing a model of the system.

  The functional description can be captured in a variety of ways. One effective approach is to use the UML tools discussed earlier. One can construct one such view through use case and class diagrams. Another view can be gained through high level state charts and activity diagrams; data and control flow diagrams commonly used in structured design methodologies give a third.

  As one formulates these diagrams and the specification, care must be taken to ensure that the specified (and ultimately modeled) states are appropriate to the application. One must make certain that the actions that are captured in the specification accurately reflect the desired (external) behavior of the system as perceived and intended by the customer. In the specification, one must ensure that the conditions or constraints on its behavior are only a function of the inputs coming into the system, the specified states, the internal events, and the appropriate time demarcation (relative or absolute).

- *Safety and Reliability*

  In formulating the safety and reliability requirements for the system, the focus is on the high level objectives of each and on the strategy for achieving those goals.

The safety considerations should address

- ✓ Safety guidelines, rules, or regulations under the governing agencies identified under the environment portion of the specification.

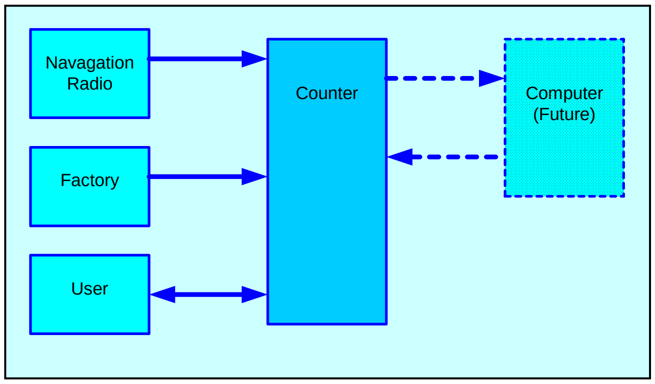
With respect to reliability, one can specify

- ✓ The system uptime goals
- ✓ Potential risks, failures, and failure modes
- ✓ Failure management strategy

Example

Starting from the trip report from *High Flying Avionics, Inc.*, which discussed their needs for a new counter, let's put the requirements specification together.

As a first step in the thought process, one extracts and summarizes the essential information from the trip report. By doing so, one can begin to focus on what should be included in the requirements specification. From the discussions with the customer, a high level sketch of the system and the environment captures the essential parts of the problem. The next step is to begin to formalize the model of the system and the environment.

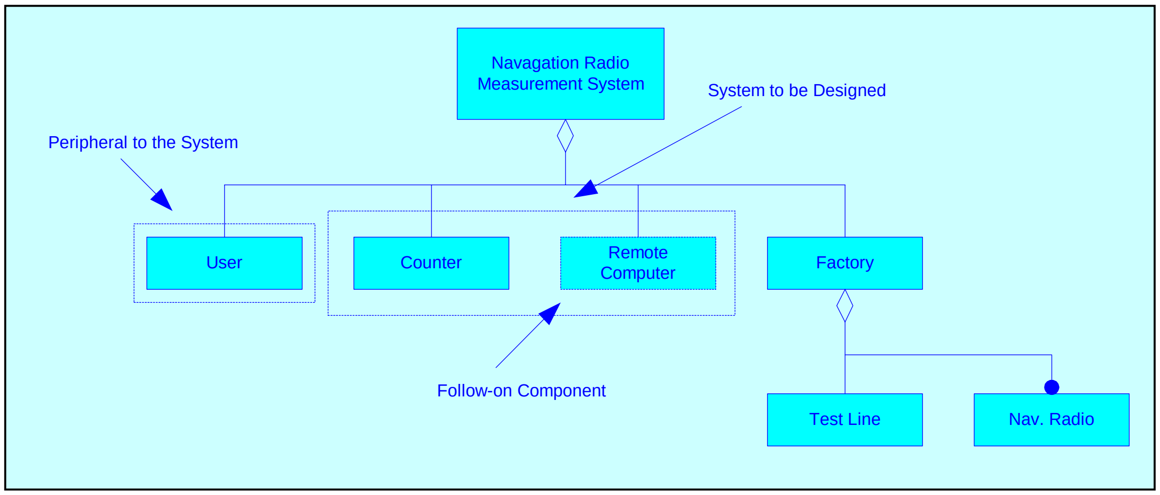


In its initial configuration, the environment contains,

- A set of navigation radios which are to be tested
- The user who is doing the testing
- The factory

Signals flow from the navigation radio to the counter, but, not the reverse. The factory has inputs to the counter as well; these include the power system and the ambient environment in the factory. The user's interaction is bidirectional. The user must select and configure the measurement to be made and then view the results once the measurement is complete. For the computer, the signal interchange with the counter similarly occurs in both directions.

In the developing model, the factory can be viewed as an aggregation of test lines and the radios to be tested. Later, the remote computer is to be added. The system to be designed, that is, the counter, interacts with all three entities. Such interaction is reflected in the following figure.



Now moving to the next level of detail,

Environment

- The customer has stated that the counter is to operate in a factory environment on any of several productions lines. Based upon such an understanding, one can make certain assumptions about temperature, power, and ambient lighting.
- Time intervals and frequencies on the navigation radios and events from equipment monitoring the production line are to be measured
- The time intervals may be either periodic or aperiodic but cannot be both.
- The polarity of the event signal to be counted can be either positive or negative going.
- The data display and the annunciation for mode and range are the only outputs expected from the counter.

- The assumption is made that the signals to be measured are independent of one another.
- In future, commands will be sent from a computer to the counter to direct its operation. Data will be sent from the counter to the computer.

Counter

- The counter must have the ability to measure time intervals, frequencies, and to count events.
- The frequencies are fixed but, span a range of values.
- The time intervals span a range of values and may be either periodic or aperiodic but cannot be both.
- The counter will support the ability for the user to manually select mode and measurement range for all input signals.
- The counter will continue to make and display the selected attribute of the signal until power to the system is turned off or until the user makes another selection.
- The counter will measure only one signal at a time.
- An event can be modeled as an aperiodic time signal.
- The design will be sufficiently flexible to allow future inclusion of the ability to send commands from a computer to the counter to direct its operation.
- The response of the counter to remote commands will be the same as its response to front panel selections with the exception that measured data will be sent from the counter to the computer as well as to the front panel display.

The next step is to formalize, in a specification, what is known about the system to be designed. The document, the S*ystem Requirements Specification*, opens with a summary of the design.

Requirements Specification for a Digital Counter

System Description

This specification describes and defines the basic requirements for a digital counter. The counter is to be able to measure frequency, period, time interval and events. The system supports three measurement ranges for each signal and two for events. The counter is to be manually operated with the ability to support remote operation in future. The counter is to be low cost and flexible so that it may be utilized in a variety of applications.

Specification of External Environment

The counter is to operate in an industrial environment in a commercial grade temperature and lighting environment.

The unit will support either line power and battery operation.

System Input and Output Specification

System Inputs

The system shall be able to measure the following signals

Frequency in three ranges:

• High range up to	150.000 MHz
• Mid range up to	50.000 KHz
• Low range up to	100.000 Hz

Period in three ranges

• High resolution up to	1.0000 ms
• Mid resolution up to	10.000 ms
• Low resolution up to	1.000 sec

Time interval in three ranges

• High resolution up to	1.0000 ms
• Mid resolution up to	10.00 ms
• Low resolution up to	1.000 sec

Events – up to 99 events in 1 minute

All signal inputs will be

- Digital data
- Voltage range 0.0 to 4.5 VDC

System Outputs

The system shall measure and display the following signals using a 6 digit display

Frequency in three ranges:

• High range up to	200.000 ± 0.001 MHz.
• Mid range up to	200.000 ± 0.001 KHz.
• Low range up to	200.000 ± 0.001 Hz

Period in three ranges

• High resolution up to	2.000 ± 0.0001 ms
• Mid resolution up to	20.00 ± 0.01ms
• Low resolution up to	2.000 ± 0.001sec

Time interval in three ranges

• High resolution up to	2.0000 ± 0.0001 ms
• Mid resolution up to	20.00 ± 0.01 ms
• Low resolution up to	2.000 ± 0.001 sec

Events in two ranges

• Fast up to	200 events in 1 minute
• Slow up to	2000 events in 1 hour

User Interface

The user shall be able to select the following using buttons and switches on the front panel of the instrument

Mode:

Frequency, Period, Time Interval, Events

Range

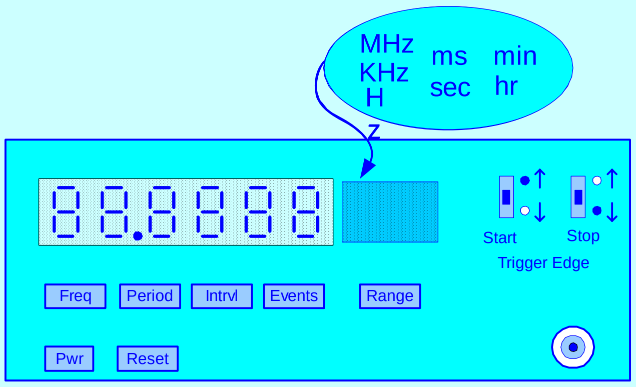
Frequency, Period, Time Interval – High, Mid, Low

Events – Fast, Slow

- Trigger Edge
  - Frequency, Period, and Events
    - Rising or Falling edge
  - Time Interval
    - Rising to rising edge
    - Falling to falling edge
    - Rising to falling edge
    - Falling to rising edge
- Reset
- Power ON/OFF

The measurement results shall be presented on a 6 digit display; leading zeros will be suppressed. The display shall be readable in direct sunlight and from any angle.

The front panel will appear as follows,



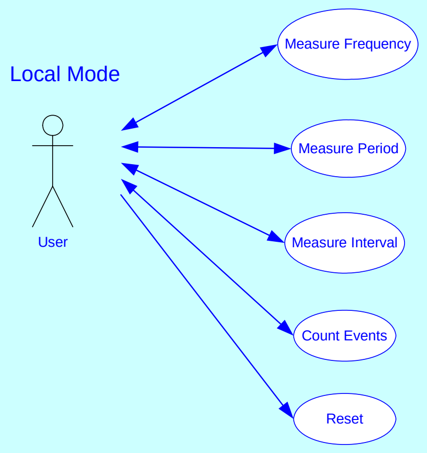
Use Cases

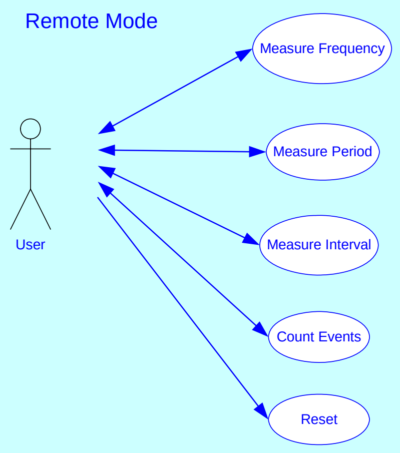
The use cases for the counter are given in the following two diagrams. The first indicates manual operation through the front panel and the second through a remote connection to a computer.

The remote option will not be included in the initial model, but will be incorporated in a later release. The time of that release is to be determined.

Execution of the selected measurement function will not depend upon how (local or remote) that function was selected.

At power ON, the default mode is *Measure Frequency*. All ranges will default to their highest value.





Measure Frequency The counter will continuously measure and display the frequency of the input signal on the currently selected range as long as the *Frequency* mode is selected.

If the frequency of the input signal exceeds the maximum allowable value on the selected range, the display will present the full scale reading and will flash.

If the frequency of the input signal is below the minimum allowable value on the selected range, the display will present a zero reading.

If the input signal returns to a value within the bounds of the range, the value of the frequency will be displayed.

The range may be changed at anytime by depressing the *range select* pushbutton.

The use may elect to measure frequency starting on the positive or negative edge

of the signal by depressing the *start trigger edge* pushbutton.

Measure Period The counter will continuously measure and display the period of the input signal on the currently selected range as long as the *Period* mode is selected.

If the period of the input signal exceeds the maximum allowable value on the selected range, the display will present the full scale reading and will flash. If the period of the input signal is below the minimum allowable value on the selected range, the display will present a zero reading.

If the input signal returns to a value within the bounds of the range, the value of the period will be displayed.

The range may be changed at anytime by depressing the *range select* pushbutton.

The use may elect to measure period starting on the positive or negative edge of the signal by depressing the *start trigger edge* pushbutton.

Measure Interval The counter will continuously measure and display the duration of the selected portion of the input signal on the currently selected range as long as the *Interval* mode is selected.

If the duration of the selected portion of the input signal exceeds the maximum allowable value on the selected range, the display will present the full scale reading and will flash.

If the duration of the selected portion of the input signal is below the minimum allowable value on the selected range, the display will display zero.

If the input signal returns to a value within the bounds of the range, the value of the duration of the selected portion of the input signal will be displayed.

The range may be changed at anytime by depressing the *range select* pushbutton.

The user may elect to commence measuring the interval on the positive or negative edge of the signal by depressing the *start trigger edge* pushbutton.

The user may elect to terminate the measurement interval on the positive or negative edge of the signal by depressing the *stop trigger edge* pushbutton.

Note that the signal duration from positive edge to positive edge or negative edge to negative edge is the same as the period of the signal.

Events The counter will continuously count and display the number of occurrences of the input signal on the currently selected range. The accumulated count will be reset to 0 at the end of the select count duration.

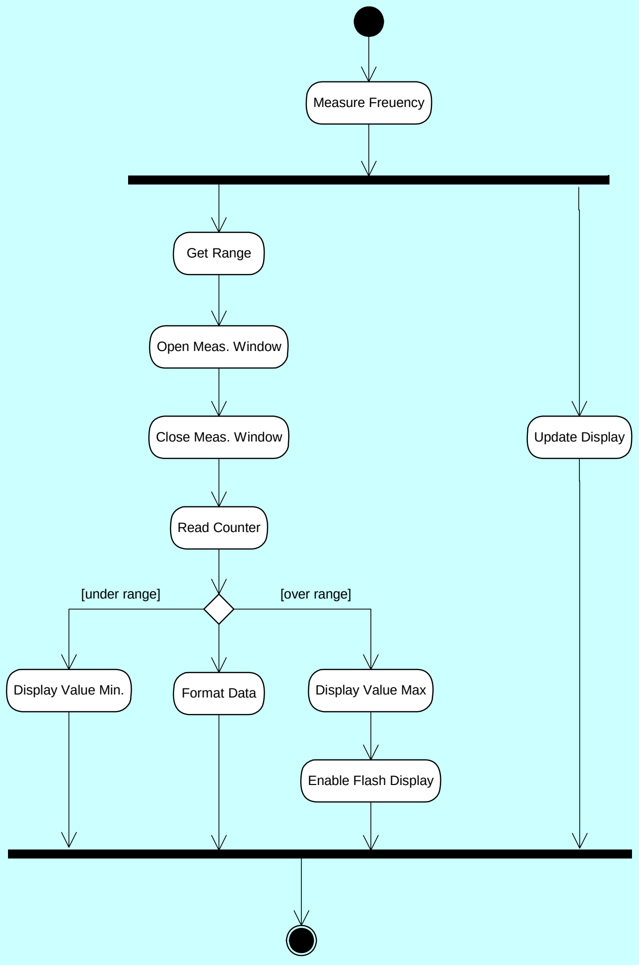
The range may be changed at anytime by depressing the *range select* pushbutton.

The user may elect to increment the count on the on the positive or negative edge of the input signal by depressing the *start trigger edge* pushbutton.

If the number of accrued counts exceeds the maximum allowable value on the selected range, the display will present the full scale reading and will flash.

System Functional Specification

The system is intended to make 4 different kinds of digital measurement in the time and frequency domains comprising frequency, period, time interval and events. The activities associated with the *Measure Frequency* mode are shown in the following diagram.



The time and frequency measurements will be implemented to provide three user selectable resolution ranges, high frequency range / shorter duration signals, a second for midrange frequency / midrange duration signals, and a third for low frequency / longer duration signals. The events measurement capability will support two selectable counting durations, shorter and longer.

For frequency, period, and events measurements, the user will be able to select either a positive or negative edge trigger. For interval measurements, the user will be able to select the polarity of the start and stop signals independently.

Operating Specifications

The system shall operate in a standard commercial / industrial environment

Temperature Range 0-85C

Humidity up to 90% RH non-condensing

Power 120 – 240 VAC 50 Hz, 60 Hz, 400 Hz, 15 VDC

The system shall operate for a minimum of 8 hours on a fully charged battery

The system time base shall meet the following specifications

Temperature stability 0-50 C

$< 6 \times 10^{-6}$

Aging Rate

90 day	$< 3 \times 10^{-8}$
6 month	$< 6 \times 10^{-7}$
1 year	$< 25 \times 10^{-6}$

Reliability and Safety Specification

The counter shall comply with the appropriate standards

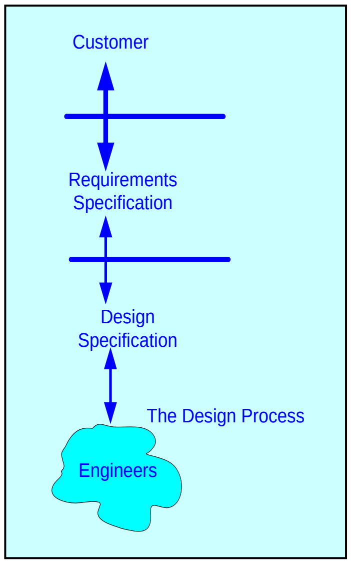
Safety: UL-3111-1, IEC-1010, CSA 1010.1

EMC: CISPR-11, IEC 801-2, -3, -4, EN50082-1

MTBF: Minimum of 10,000 hours

12.7 The System Design Specification

The *System Design Specification* is based upon the *System Requirements Specification*. It specifies the *how* of the design not the *what.* The specification is written in the designer's language and from the designer's point of view. It serves as bridge between the customer and the designer as we see in our evolving graphic.



The *Requirements Specification* provided a view from the outside of the system looking in; the *Design Specification* provides a view from the inside looking out as well. Notice also that the *Design Specification* has two masters,

- It must specify the system's public interface from inside the system.
- It must specify *how* the requirements defined for and by the public interface are to be met by the internal functions of the system.

We've seen that the *Requirements Specification* is written in less formal terms with the intent of capturing the customer's view of the product. The *Design Specification* must formalize those requirements in precise, unambiguous language. Putting the inevitable changes that occur during the lifetime of any project aside for the moment, the design specification should be sufficiently clear, robust, and complete that a group of engineers could develop the product without ever talking to the author of the specification.

Design Note,

A good litmus test of the viability of a design specification is the question, 'If I send this to my colleague (who is working for one of our subcontractors), will he or she understand this?' If answer is no, the specification should be re-examined.

12.7.1 The System

As a part of formalizing and quantifying the system's requirements, one must attach concrete numbers, tolerances, and constraints to all of system's input and output signals. All timing relationships must be defined. The system's functional and operational behaviors are described in detail.

12.7.1.1 Quantifying the System

The quantification of the system's characteristics begins with the inputs and outputs, based upon the specified requirements. The necessary technical details are added to enable the engineer to accurately and faithfully execute the actual design.

- *System Inputs and Outputs*
  For each I/O variable, the following are specified
  - ✓ The Name of the signal
  - ✓ The use of the signal as an input or output
  - ✓ The nature of the signal as an event, data, state variable, etc.

    Starting with the requirements specification, we provide detailed descriptions as necessary and incorporate any additional technical or technological constraints that may be needed.
  - ✓ The complete specification of the signal including nominal value, range, level tolerances, timing, timing tolerances.
  - ✓ The interrelationships with other signals including any constraints on those relationships.
- *Responsibilities – Activities*
  - ✓ Functional and Operational Specifications

    The functional and operational specifications that will quantify the dynamic behavior of the system are now formulated. The functional requirements specification identifies the major functions that the system must perform from a high level view. The operational specification endeavors to capture specific details of how those functions behave within the context of the operating environment.

    The manner in which a particular function must operate, the conditions imposed on the operation, and the range of that operation are now captured. The specification must consider concrete numbers – precisions and tolerances.

    All variables in the functional specification, all operating conditions, and all ordinary and extraordinary operating modes must be quantified. The specification may include domain specific knowledge that is proprietary or heuristically known to customer. Such knowledge can be very important to the design.

In stating the specific design requirements for the system, one can use tables, equations or algorithms, formal design language, or pseudo code, flow diagrams, or detailed UML diagrams such as state charts, sequence diagrams, and timelines. Schematics, code, or parts lists except in limited circumstances are not included.

✓ Technological (and Other) Specifications

The technological portion includes all detailed and concrete specifications that are relevant to the design of the system hardware and software. Six areas that should be considered can easily be identified.

1. Geographical constraints

   Distributed applications can span a single room, expand to include a complete factory, or encompass several countries. Consequently, one must address both the technical items such as interconnection topologies, communications methods, restrictions on usage, and environmental contamination as well as non-technical matters such as costs associated with the physical medium and its installation.

2. Characterization of and constraints on interface signals

   The assumption is made that signals between the system and the external world are electrical, optical, or wireless or they can be converted into or from such a form. The necessary physical characterization of each is obviously going to depend upon the type of signal. That is, an electrical signal is specified differently from an optical signal.

   Since many of the interface signals may be driven by the external environment, potentially they are beyond the designer's control. Therefore, it's important to gain as much information about them as possible.

3. User interface requirements

   If the system interfaces to such external world devices as medical or instrumentation equipment, how information is presented and whether there are any relevant and associated protocols must be considered. There may also be standards that govern how such information must be presented.

Consider the significant risk that would arise if each avionics vendor presented critical flight information and controls to the aircraft pilot in a different way. The near disaster at Three Mile Island arose, in part, because of the confusion caused by too much information.

4. Temporal constraints

   The system may have to perform under hard or soft real-time constraints. Such constraints may specify delays on signals originating from external entities, responses to system outputs by external entities, and/or internal system delays.

5. Electrical Infrastructure considerations

   There must be a specification for and electrical characteristics of any of the electrical infrastructure. Included in this portion of the specification are power consumption, necessary power supplies, tolerances and capacities of such supplies, tolerance to degraded power, and power management schemes.

- *Safety and Reliability*

In formulating the design requirements for the safety and reliability of the system, the focus shifts to the detailed objectives of each and on the strategy for achieving those goals.

Safety considerations should address

- ✓ Understanding and specifying any environmental and safety issues.

The reliability specification should include

- ✓ Requirements for diagnostic tests, remote maintenance, remote upgrade and their details.
- ✓ Concrete numbers for MTTF and MTBF of any built in self test circuitry.
- ✓ There must be concrete numbers for MTTF and MTBF of the system itself.
- ✓ System performance under partial or full failure must be considered.

Let’s now bring everything together,

Example Continued…

We’ll now continue with the development of the counter. The *Design Specification* will follow, but extend, what has been captured in the *Requirements Specification*. The focus will now be on providing specific numbers, ranges, and tolerances for signals that are within the system.

Once again, we’ll put together any thoughts about the environment and the system prior to writing the specification.

Environment

Specifications relating to the environment have been discussed earlier. There are no changes here.

Counter

- When specifying measurement and stimulus equipment, the specifications for that equipment are generally 10 times (one order of magnitude) better than for the signals that must be measured or generated.

  That margin is provided when specifying the range and tolerances on the counter’s measurement capabilities.
- Specifications on counting events are based upon the granularity of the timing of the interval during which the events are counted.
- The values to be displayed at the measurement boundaries are now defined.

The next step is to provide any additional detail that may be needed and to fully quantify the counter specifications.

Design Specification for a Digital Counter

System Description

This specification describes and defines the detailed design requirements for a digital counter. The counter is to be able to measure frequency, period, time interval and events. The system supports three measurement ranges for each signal and two for events. The counter is to be manually operated with the ability to support remote operation in future. The counter is to be low cost and flexible so that it may be utilized in a variety of applications.

Specification of External Environment

The counter is to operate in an industrial environment in a commercial grade temperature and lighting environment.

The unit will support either line power and battery operation.

Specific details are included under Operating Specifications.

System Input and Output Specification

System Inputs

The system shall be able to measure the following signals

Frequency in three ranges:

• High range up to	150.000 MHz
• Mid range up to	50.000 KHz
• Low range up to	100.000 Hz

Period in three ranges

• High resolution up to	1.0000 ms
• Mid resolution up to	10.000 ms
• Low resolution up to	1.000 sec

Time interval in three ranges

• High resolution up to	1.0000 ms
• Mid resolution up to	10.00 ms
• Low resolution up to	1.000 sec

Events

• Events to	99 per minute
• Signal level	0-4.0 V ± 0.5 V
• Transition time	$10 \text{ ns} \le \tau_{rise}, \tau_{fall} \le 50 \text{ ns}$

Voltage Sensitivity

- 50 mV RMS to ± 5.0 V ac signal + dc signal

All signal inputs will be

- Digital data
- Voltage range 0.0 to 4.5 VDC

System Outputs

The system shall measure and display the following signals using a 6 digit display

Frequency in three ranges:

- High range
  - Measure: 0 – 200 ± 0.0001 MHz
  - Display: 0 – 200.000 MHz.
- Mid range up to 200.000 KHz.
  - Measure: 0 – 200 ± 0.0001 KHz
  - Display: 0 – 200.000 KHz.
- Low range up to 200.000 Hz
  - Measure: 0 – 200 ± 0.0001 Hz
  - Display: 0 – 200.000 Hz.

Period in three ranges

- High resolution up to 2.0000 ms
  - Measure: 0 – 2.00000 ± 0.00001 ms
  - Display: 0 – 2.0000± 0.0001 ms
- Mid resolution up to 20.00 ms
  - Measure: 0 – 20.0000 ± 0.0001 ms
  - Display: 0 – 20.000± 0.001 ms
- Low resolution up to 2.000 sec
  - Measure: 0 – 2.0000 ± 0.0001 sec
  - Display: 0 – 2.000 ± 0.001 sec

Time interval in three ranges

- High resolution up to 2.0000 ms
  - Measure: 0 – 2.00000 ± 0.00001 ms
  - Display: 0 – 2.0000± 0.0001 ms
- Mid resolution up to 20.00 ms
  - Measure: 0 – 20.0000 ± 0.0001 ms
  - Display: 0 – 20.000± 0.001 ms
- Low resolution up to 2.000 sec
  - Measure: 0 – 2.0000 ± 0.0001 sec
  - Display: 0 – 2.000 ± 0.001 sec

Events in two ranges

- Fast up to 200 events in 1 minute
  - Measure: 0 – 200 ± 1 event
  - Display: 0 – 200 ± 1 event
- Slow up to 2000 events in 1 hour
  - Measure: 0 – 2000 ± 1 event
  - Display: 0 – 2000 ± 1 event

User Interface

The user shall be able to select the following using buttons and switches on the front panel of the instrument.

The mode select push buttons are interlocked to ensure that only one mode at a time can be selected.

Mode:

Frequency, Period, Time Interval, Events

Range

Frequency, Period, Time Interval – High, Mid, Low

Events – Fast, Slow

Trigger Edge

Frequency and Period

Rising or Falling edge

Time Interval

Rising to rising edge
Falling to falling edge
Rising to falling edge
Falling to rising edge

Reset

The reset button will clear the display to all 0's and reset the internal timing/counting chain.

The counter will be placed in the *frequency* mode with the *range* set to KHz, and the *trigger edge* set to *rising*.

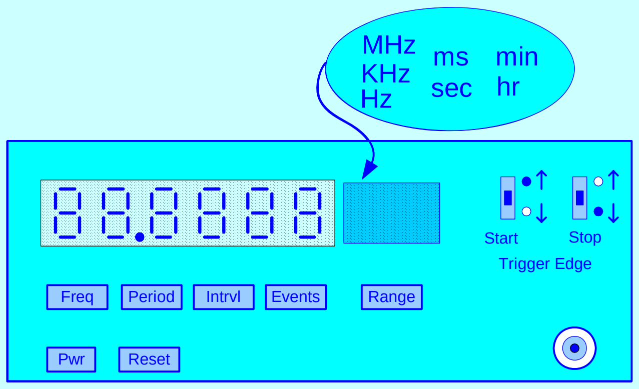
Power ON/OFF

The measurement results shall be presented on a 6 digit LED display; leading zeros will be suppressed.

The decimal point will move to reflect the proper value for the range selected as the range push button is pressed.

The display shall be readable in direct sunlight and from any angle.

The front panel will appear as follows,



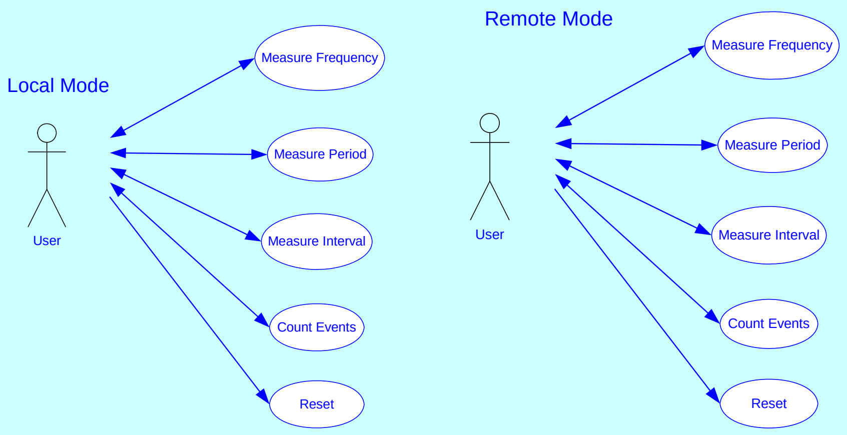
Use Cases

The use cases for the counter are given in the following two diagrams. The first indicated manual operation through the front panel and the second through a remote connection to a computer.

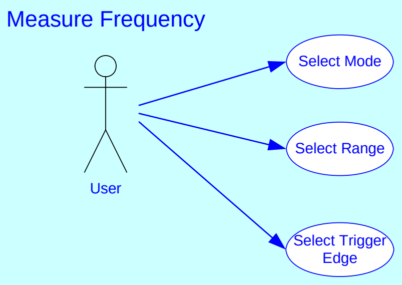
The remote option will not be included in the initial model, but will be incorporated in a later release. The time of that release is to be determined.

Execution of the selected measurement function will not depend upon how (local or remote) that function was selected.

At power ON, the default mode is Measure Frequency. All ranges will default to their highest value.



Measure Frequency The counter will continuously measure and display the frequency of the input signal on the currently selected range as long as the *Frequency* mode is selected. The following use cases are defined for the *measure frequency* mode.



If the frequency of the input signal exceeds the maximum allowable value on the selected range, the display will flash and will present one of the following values based upon the selected range,

- 200.000 MHz
- 200.000 KHz.
- 200.000 Hz

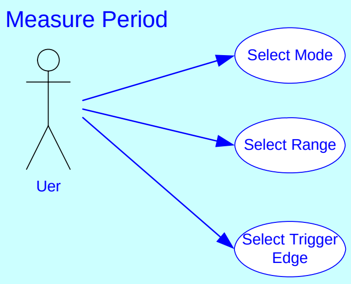
If the frequency of the input signal is below the minimum allowable value on the selected range, the display will present a zero reading.

If the input signal returns to a value within the bounds of the range, the value of the frequency will be displayed.

The range may be changed at anytime by depressing the *range select* pushbutton.

The use may elect to measure frequency starting on the positive or negative edge of the signal by depressing the *start trigger edge* pushbutton.

Measure Period The counter will continuously measure and display the period of the input signal on the currently selected range as long as the *Period* mode is selected. The following use cases are defined for the *measure period* mode.



If the period of the input signal exceeds the maximum allowable value on the selected range, the display will flash and will present one of the following values based upon the selected range,

- 2.0000 ms
- 20.000 ms
- 2.000 sec

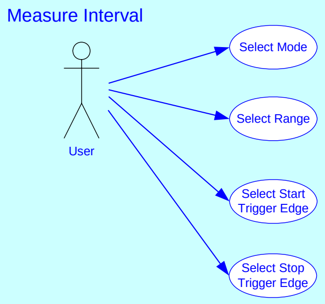
If the period of the input signal is below the minimum allowable value on the selected range, the display will present a zero reading.

If the input signal returns to a value within the bounds of the range, the value of the period will be displayed.

The range may be changed at anytime by depressing the *range select* pushbutton.

The use may elect to measure period starting on the positive or negative edge of the signal by depressing the *start trigger edge* pushbutton.

Measure Interval The counter will continuously measure and display the duration of the selected portion of the input signal on the currently selected range as long as the *Interval* mode is selected. The following use cases are defined for the *measure interval* mode.



If the duration of the selected portion of the input signal exceeds the maximum allowable value on the selected range, the display will flash and will present one of the following values based upon the selected range,

- 2.0000 ms
- 20.000 ms
- 2.000 sec

If the duration of the selected portion of the input signal is below the minimum allowable value on the selected range, the display will display zero.

If the input signal returns to a value within the bounds of the range, the value of the duration of the selected portion of the input signal will be displayed.

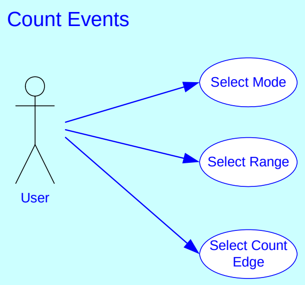
The range may be changed at anytime by depressing the *range select* pushbutton.

The user may elect to commence measuring the interval on the positive or negative edge of the signal by depressing the *start trigger edge* pushbutton.

The user may elect to terminate the measurement interval on the positive or negative edge of the signal by depressing the *stop trigger edge* pushbutton.

Note that the signal duration from positive edge to positive edge or negative edge to negative edge is the same as the period of the signal.

Events The counter will continuously count and display the number of occurrences of the input signal on the currently selected range. The accumulated count will be reset to 0 at the end of the select count duration. The following use cases are defined for the *count events* mode.



If the number of accrued counts exceeds the maximum allowable value on the selected range, the display will flash and will present one of the following values based upon the selected range,

- 200 min
- 2000 hour

The range may be changed at anytime by depressing the *range select* pushbutton.

The user may elect to increment the count on the on the positive or negative edge of the input signal by depressing the *start trigger edge* pushbutton.

System Functional Specification

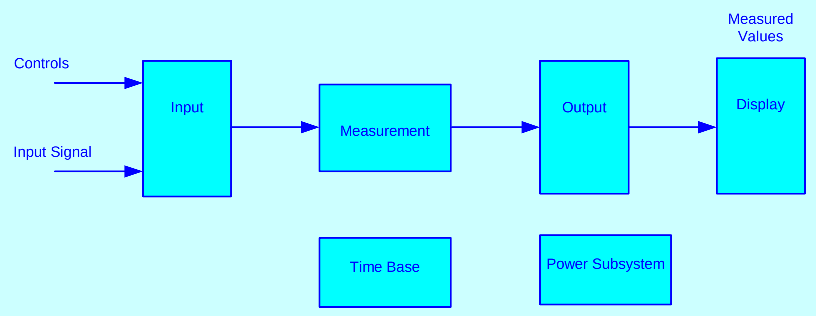
The system is intended to make 4 different kinds of digital measurements comprising frequency, period, time interval and events.

The time and frequency measurements will be implemented to provide three user selectable resolution ranges, high frequency range / shorter duration signals, a second for midrange frequency / midrange duration signals, and a third for low frequency / longer duration signals. The events measurement capability will support two selectable counting durations, shorter and longer.

For frequency, period, and events measurements, the user will be able to select either a positive or negative edge trigger. For interval measurements, the user will be able to select the polarity of the start and stop signals independently.

The system will be designed so as not to preclude the incorporation of a remote access option in future.

The system comprises 6 major blocks as given in the following block diagram.



Input Subsystem – the input subsystem shall provide the ability for the user to select any of the measurement functions, ranges, and triggering polarities. The subsystem also selects and routes the input signal to the appropriate portion of the measurement subsystem.

Output Subsystem – the output subsystem implements the range, edge selection, control information, and data formatting for proper presentation on the front panel display.

Time Base – the time base subsystem is a phase locked loop and divider chain driven from a 100 MHz crystal oscillator. This subsystem will provide two clock phases to drive the internal control and decision logic. Each phase will be 200.0000 ± 0.0001 MHz.

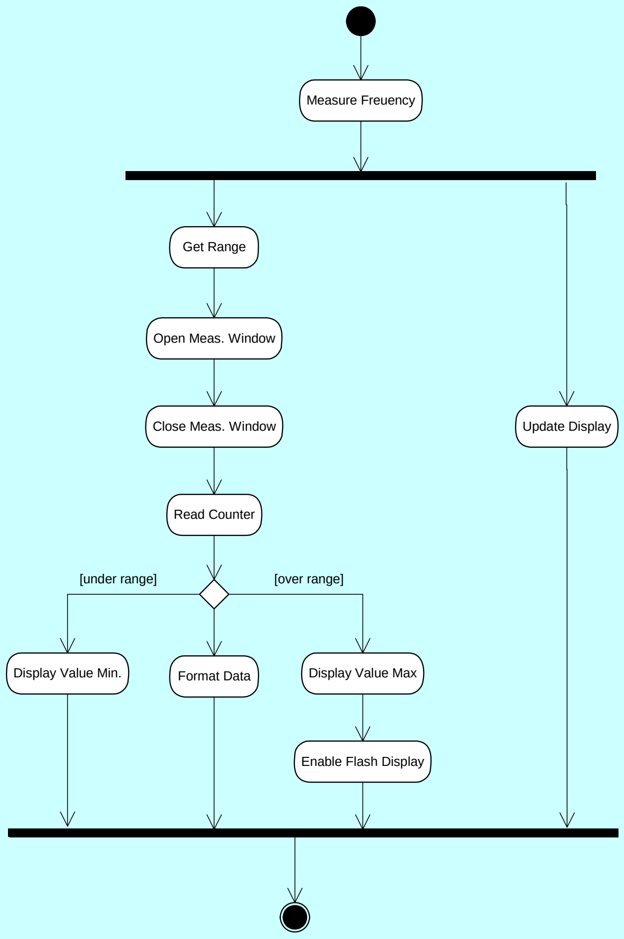
The time base will also provide the following frequencies that are used to define the measurement windows for the events and frequency measurements and provide the counting frequencies for the time interval and period measurements.

- Frequency – 200.0000 ± 0.0001 MHz
- Period – 100.0000 ± 0.0001 MHz
- Time Interval – 100.0000 ± 0.0001 MHz
- Events – 10.00 ± 0.01Hz

Measurement Subsystem – the measurement subsystem provides the logic and control to execute the measurements of time and frequency.

- The frequency measurement will be implemented by opening a window for 1.00 ± 0.01 seconds. During the time the window is open, the measurement subsystem will gate the unknown input frequency into a 7 stage BCD counter. When the window closes, the counter will contain the value of the unknown frequency.

The activities that are necessary to execute a frequency measurement as given in the following diagram.



- The period and time interval measurements will be made by opening a window on the specified signal edge. While the window is open, a frequency of 100.0000 ± 0.0001 MHz will be gated into a 7 stage BCD counter. When the window closes, the counter will contain the values of the unknown time interval.
- The counter will contain the number of events that occurred during the measurement interval.

The events measurement will be made by opening a window for 1.00 ± 0.01 seconds for the fast mode and 3600.0 ± 0.1 seconds for the slow mode. During the time the window is open, the measurement subsystem will gate the unknown input to a 4 stage BCD counter. When the window closes, the counter will contain a measure of the number of events that occurred during the time interval.

Power Supply Subsystem – the power supply subsystem will provide the following voltages at the specified current levels to the internal logic.

+5.0 ± 0.01 VDC @ 10 A

+15.0 ± 0.01 VDC @ 500 mA

-15.0 ± 0.01 VDC @ 500 mA

At power on, there shall be a negative going reset signal. That signal shall remain in the low state for a minimum of 10 ms and shall have the ability to sink up to 1A.

Display – the instrument display shall display the results of the selected measurement on a 6 digit, 7 segment red LED display. The layout of the major features and functions is given in the earlier diagram.

Operating Specifications

The system shall operate in a standard commercial / industrial environment

Temperature Range 0-85C

Humidity up to 90% RH noncondensing

Power Automatic line voltage selection

- 100 – 120 VAC ± 10% 50, 60, 400 Hz ± 10%
- 220 – 240 VAC ± 10% 50, 60 Hz ± 10%

The system shall operate for a minimum of 8 hours on a fully charged battery

Net weight / size 2.75 kg, H: 90 mm x W: 200mm x D: 300 mm

The system time base shall meet the following specifications

Temperature stability 0-50 C

$< 6 \times 10^{-6}$

Aging Rate

90 day	$< 3 \times 10^{-8}$
6 month	$< 6 \times 10^{-7}$
1 year	$< 25 \times 10^{-6}$

Reliability and Safety Specification

The counter shall comply with the appropriate standards

Safety: UL-3111-1, IEC-1010, CSA 1010.1

EMC: CISPR-11, IEC 801-2, -3, -4, EN50082-1

MTBF: Minimum of 10,000 hours

12.8 System Specifications versus System Requirements

Examining the different steps that have been outlined up to this point, there appears to be a lot of duplication. It seems that the *System Design Specification* and *System Requirement Specification* are just different names for the same thing. They're not; requirements and specifications are fundamentally different types of descriptions.

Requirements - Give a description of something wanted or needed. They are a set of needed properties.

Generally requirements come from the marketing or sales department and they represent the customer's needs. The requirements definition and specification is not concerned with the internal organization of the system. It's intended to describe w*hat* a system must do and *how well* it has to do it, not *how* it does it. The *System Design Specification* is generated by engineering as an answer to and a description of how to implement the requirements. Then the two groups negotiate and iterate until the requirements and specifications are consistent.

Specification - Is a description of some entity that has or implements those properties.

The system specification is a means of translating the description of needs into a more formal structure and model.

None-the-less, it seems that every part of the design needs another specification. Certainly, this is true. Specifications can and do exist at various levels as the design is refined and elaborated. Different things must be quantified and at different levels of detail during different phases of the product development. The *System Design Specification* may require that a inter system communication channel transfer data at the rate of 10,000 bytes per second at a specific bit error rate. The detailed *Hardware* and *Software*

Specifications establish the requirements and constraints on their respective components to be able to meet those specifications.

A specification is a precise description of the system that meets stated requirements. Ideally a specification document should be

- Complete
- Consistent
- Comprehensible
- Traceable to the requirements
- Unambiguous
- Modifiable
- Able to be written

The specification should be expressed in as formal a language or notation as possible yet readable. Ideally, it should also be executable. A *System Specification* should focus precisely on the system itself. It should provide a complete description of its externally visible characteristics, that is, its public interface. External visibility clearly separates those aspects that are functionally visible to the environment in which the system operates from those aspects of the system that reflect its internal structure.

12.9 Partitioning and Decomposing a System

At this point in the design cycle, all of the system requirements have been identified, captured and formalized into the *System Design Specification*. The next step is to move inside the system and begin the process of specifying and designing the functionality that gives rise to the external behavior.

Throughout all of the previous discussions, modularity and encapsulation have been repeatedly stressed. We'll look first at why such an approach is recommended and then at what should be considered as the process of decomposing and ultimately partitioning the system into hardware and software modules proceeds.

12.9.1 Initial Thoughts

So, to the first question, 'Why do we do this?' Reuse is one important reason. With each new design, one should always look to the previous project as well as the next one. What can be used from the last project to expedite the development of this one? How can the current design be implemented to support a future feature? Are there parts of this design that can be used in future projects?

Second, many compilers generate object code in segments, one for each module. Such actions may place size restrictions on the individual modules. Poor module builds can significantly affect memory accesses, increase cache misses, promote thrashing and significantly reduce performance.

Thirdly, often, work assignments are made on a module by module basis. Module boundaries should be defined so as to minimize interfaces amongst different parts of the system. Such a practice simplifies the process of subcontracting some of the work as well. Security issues also play a role when subcontracting is considered. Whether working for a toy company or on a sensitive government project, one needs to consider what information to make available to outside vendors. By properly decomposing a system, the portions that can be outsourced and those for which control over should be retained can be more easily identified.

Fourthly, the modules should be packaged with the goal of stabilizing the module interfaces during the early part of the design.

Fifthly, partitioning the system into well defined loosely coupled modules helps to ensure a safe and robust design. Such an approach helps to prevent a failure in one part of the system from propagating into and affecting another.

The importance of partitioning a new design should be evident; the next step is to examine the process for doing so. The process starts with the top-level system then *progressively refines* that model into smaller and more manageable pieces that can more easily be designed and built.

Initially, the focus is on a functional view of the system rather than specific pieces of hardware and software. It's important to understand and to capture the behavior at a high level first. The next step will then be to map those functions, that functionality, onto the hardware and software as necessary to satisfy the constraints identified during the initial phases of the design. Partitioning is important during the early stages of the development of the system to aid in attacking the complexities of a large system and then later as a guide in arriving at a sound physical architecture.

As we begin to think about organizing the system into the collection of pieces that will implement the customer's requirements, one should look at the problem from both a high level view *and* from a more detailed view. It's important to remember that developing a partition is not a one-time process; it isn't necessary to be perfect the first time. The partitioning process will probably need to be done several times before a satisfactory and workable decomposition is achieved.

Prior to beginning the system partition, there are some general thoughts.

1. Remember that with every rule or guideline, there must always be room for exceptions.
2. Each module should solve one well-defined piece of the problem.
   Mixing functionality across modules makes all aspects of the development and support process much more difficult. By doing so, one can easily create noodle hardware and spaghetti code. Future changes to such modules will very difficult to implement and easily lead to unexpected side effects and unrelated pieces of the system suddenly not working.

   While it's desirable to have well-defined modules, with simple interfaces, that solve nicely encapsulated pieces of the problem, sometimes in embedded applications one isn't able to do so because of performance or economic constraints.
3. The system should be partitioned so that the intended functionality of each module is easy to understand.

   If the design can be understood by other parties, then they will be able to maintain it and to extend it as necessary throughout the product's lifetime. Remember, over half of the engineers who are involved in embedded systems design do not do new designs; they maintain and enhance existing designs.

   During development, easy to understand designs will lead to fewer surprises as the design nears completion. All interested parties should be able to follow the design and comment as the process unwinds. A design that is too complex quickly discourages early criticism. People won't take the time to learn what the system is to do. Unfortunately, such early acceptance often is replaced by later rejection and potentially major redesign efforts. Although it's important to be proud of one's work, one should always seek out others constructive ideas.

4. Partitioning should be done so that connections between modules are only introduced because of connections between pieces of problem.

   Don't put a piece of functionality into a module just because there's nowhere else for it to go.

5. Partitioning should assure that connections between modules are as independent as possible.

6. Once again, keep like things together. Such a practice helps to reduce errors. Partitioning is also done to help meet the economic goals of the design.

When forming partitions, the process must be considered from a number of viewpoints. Taking only single point of view or neglecting any one can have significant long term effects. At the end of the day, the system may meet neither the customer's expectations nor the performance specifications.

As the decomposition process proceeds, the design should first be considered from a *functional* point of view. The outcome from the decomposition steps is a functional model and that can be used to define the system architecture. Among the many things that should be considered, two that should appear early in the process are the *coupling* and the *cohesiveness* of the modules into which the system is being decomposed. The goal is to develop *loosely coupled, highly cohesive modules*. Let's see what these mean.

12.9.2 Coupling

Coupling is a heuristic that provides an estimate of how interdependent the modules are. Tightly coupled modules will generally utilize shared data or interchange control information. As module interdependence increases, so does the complexity of managing those modules, and the more difficulty one will have,

- Debugging the design during development
- Troubleshooting the system in the event of field failures,
- Maintaining the modules and system, and
- Modifying the design to add features or capabilities.

The major goal is to make the system's modules as independent as possible – the goal is to reduce or minimize coupling.

Design Heuristic

The lower the coupling, the better job that has been done during partitioning.

Here are several things to think about during the early stages of the design to help to reduce coupling:

1. Eliminate all unessential interaction between modules.

   If a particular piece of functionality or shared parameter is not a part the intended task of two modules, then eliminate it.

2. Minimize the amount of essential interaction between modules.

   While this sounds the same as the previous point, it's not. If an early analysis establishes that some interaction with another module is necessary, effort should be made to reduce the complexity of that required interface. The goal is to keep things simple.

   Some of the ways to help to reduce complexity include:

   a. Reduce the number of interconnections between modules and thereby reduce the number of pieces of data that must flow between modules.
   b. Try to take the most direct route to a signal or piece of data as appropriate.

      There are some cases for which the best implementation is to use a proxy as an interface to a signal or piece of data. In general, however, it's best to reduce the number of modules involved.
   c. In general, avoid using shared global variables. A better method is to pass data into a module via its parameter list or calling interface.

      With embedded applications, however, there are times when such sharing is critical to meeting time constraints.

d. Avoid arcane interconnections between or amongst modules. A guiding principle underlying all design is to keep things simple.

e. Don't hard code values into a module's parameter list or calling interface unless absolutely necessary. We must do so on occasion when an interface module or port must be at a specific address location; don't make this a general practice.

3. Loosen the essential interaction between modules, if possible.

   Unless the environment demands a high degree of coordination between several modules to accomplish a task or to ensure error free communication, simply pass the module the information necessary to get the job done. Thereafter, wait for an indication that the task has completed. Execute some other part of the task.

12.9.3 Cohesion

An idea related to *coupling* is *cohesion.* The notion of coupling addresses the partitioning of a system; cohesion addresses bringing the pieces together. Cohesion is measure of strength of the functional relatedness of elements in a module. The goal is to create strong, highly cohesive modules whose elements are genuinely and tightly related to one another. Conversely, elements should not be strongly related to elements in another module. We want to *maximize* cohesion and *minimize* coupling.

The use of cohesion as a reliability and quality metric has been around since the mid 1960s. A number of years of refinement and integration of the ideas of many people studying various designs and design approaches led Constantine and Yordon (Y and C 1979 Page-Jones) to formulate a cohesion scale based upon an ease of maintenance metric.

Let's look at several different kinds of cohesion.

Functional Cohesion – The module implements a single task and all comprising elements contribute to the execution of that one task.

Sequential Cohesion – The module implements a task as a sequential set of procedures. The output data of each procedure becomes the input data to the next. All of the comprising elements are involved in one of those procedures.

Communicational Cohesion – The module implements a task that has a number of procedures working on the same set of input data such as an image processing task.

Procedural Cohesion – The module implements a number of procedures that may or may not be related to a common activity. Control, rather than data, flows from one procedure to the next.

Temporal Cohesion – The module implements a number of unrelated procedures or activities that are sequentially ordered in time.

Logical Cohesion – The module implements a number of procedures that are possible alternative methods for accomplishing a task. A subset of those alternatives is selected by an outside user to actually execute the task.

Co-incidental Cohesion – The module aggregates a number of unrelated procedures. Such cohesion - or lack thereof should not be used.

We compare the different kinds of cohesion and coupling from several different perspectives in the following. The ranking is Excellent/Easy = 5…Poor/Difficult = 1

Cohesion	***Coupling***	***Ease of Modification***	***Ease of Understanding***	***Ease of Maintenance***
Functional	5	5	5	5
Sequential	4	4	4	3-4
Communicational	3	3	3	3
Procedural	2-3	2-3	2-3	2
Temporal	1	3	3	2
Logical	1	1	2	1
Co-incidental	1	1	1	1

Table

Cohesion and Coupling in System Designs

Cohesion and coupling analyses provide a good set of metrics by which to begin to assess the high level architectural aspects of a design. Remember, however, that both are guidelines. The work to ensure that the design is solid and that it's thoroughly tested still needs to be done.

There are plenty of good designs that require tightly coupled modules. CDMA cell phones are a good example of this. One can have tightly coupled multiprocessor designs as well as designs based upon message passing, the implication is not that one design is right or wrong, or better than the other, it is just how it was done to meet the requirements.

12.9.4 More Considerations

With today's systems, a *spatial* point of view is often essential. This is an external view of the system and it yields a distributed functional architecture. With such a view, performance and communication costs are taken into consideration. Closely associated with the spatial viewpoint is that of *resource* allocation; again, an external view. Such efforts result in a "resource architecture". Once again, performance, costs, and dependability are factors that must be considered.

Finally, one must consider the *hardware* and the *software*. Decomposition becomes a design process that leads to a hardware architecture as was discussed earlier. Now performance must be considered. As embedded developers, we are playing a direct role in the design and selection of the hardware platform as well as the software environment. Intelligently making trade-offs in these two areas can be take us a long way towards developing a safe, robust, and high quality / high performance system.

12.10 Functional Design

The purpose at this stage of the design is to find an appropriate internal *functional* architecture for the system. We are beginning to formulate *how* the requirements that have been identified can be implemented. The current focus is on analyzing the problem. Through such analysis, a somewhat loose understanding of the design can be transformed into a precise description. The result of such a process is a detailed textual or graphical description of the system. The end result is a complete consistent functional definition of the required tasks.

To establish an appreciation of a functional model of a system, consider an aircraft. If an aircraft is the system to be designed, the top level functional model should probably not consist of more than 3 major functions: *take-off, fly,* and *land*. With such a view, we make no statements about such issues as the support structure for the aircraft (wheels, skies, pontoons), the propulsion system (jet, rocket, propeller), or the method of lift (wings - conventional aircraft or blade - helicopter). Early on, these are not important. Such decisions can be postponed until later. The advantage of such an approach is early flexibility – time to explore before beginning to constrain the system. A functional description simply formalizes the intended behavior of the design.

The functional description should be written to be understood by those knowledgeable in the application domain and by those who will do the hardware and software development. The specification must also be such that it can be reviewed by the many diverse and interested parties and tested against reality. If it's too complex to read and understand, no one will read it. When the completed project is delivered, it's too late to discover that the customer's view and developer's view of reality are totally different.

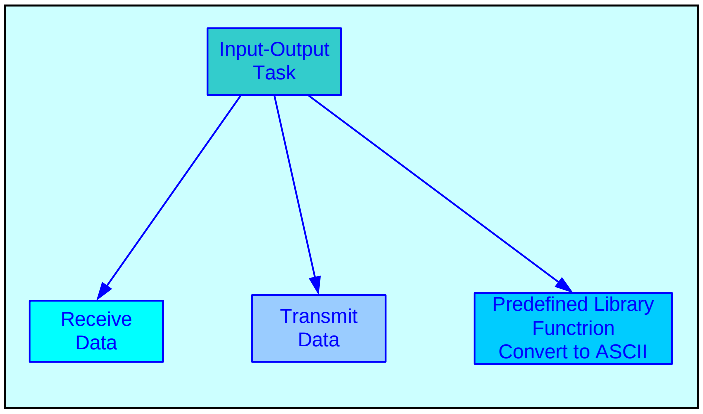
A first functional decomposition is carried out based upon a search of essential internal variables and events in the system. The design process then consists of successive refinements or decompositions for each function (using exactly the same process) until elementary or leaf functions are obtained. Such decomposition forms a *functional model* of the system. The model expressed, by the collection of such functions, should be sufficient to verify the design quality and to evaluate system behavior and performance.

During modeling and verification, the system's operations and associated performance requirements can be allocated to the internal functions and the relations between such functions defined. Such a process also allows one to estimate the expected performance of the system.

As with the requirements specification, ideally, the functional model should be executable so as to permit verification with respect to the specification. There are tools today that will allow us to do this. One such tool is a behavioral Verilog model. UML is also beginning to make executable models a reality.

The functional model is different from the specification and also from the physical architecture that will be developed next. The specification describes the *external* behavior of the system; the functional model targets the *internal* behavior that will lead that the external. The architectural model addresses the physical hardware and software components onto which the functions are mapped.

In the following figure, is a first level decomposition of a simple input / output task. The system must receive data from and transmit data to the outside world. Associated with the task, is a code conversion to ASCII.



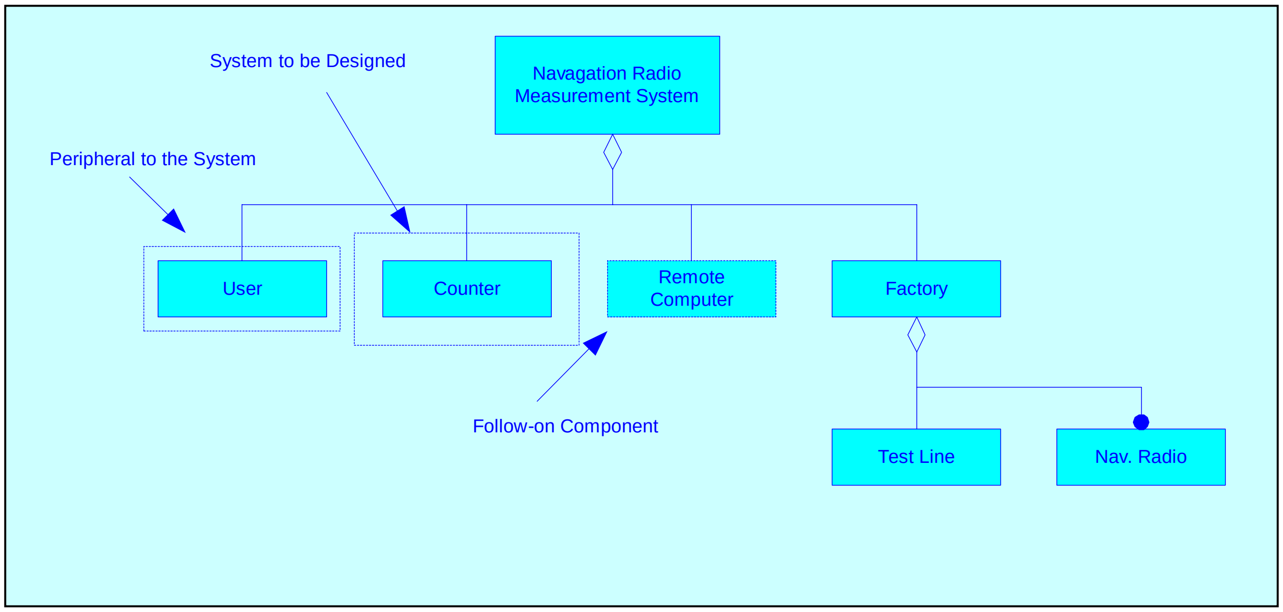
Each of these functions may be further decomposed as necessary. If required, the second level functions may also be successively refined to give the level of detail needed to understand and to execute the design.

The next step in the analysis is to identify the messages that flow between the user or other active external objects and the system as well as the internal signals that flow between the major functional blocks. We identify how the user will interact with the system to make it do what it is intended to do.

Let's now apply our understanding of partitioning to the functional design of counter system. First and foremost…we must continue to postpone the idea of working with the specific data structures, bits, bytes, microprocessors or array logics for a while longer. While important later in the process, at the moment, they limit explorations and can bias the functional decomposition of the system

Example Continued…

The first diagram presents an aggregation of the objects in the system. That aggregation includes both the environment and the counter being designed.



The model of the measurement system is expressed as a collection of

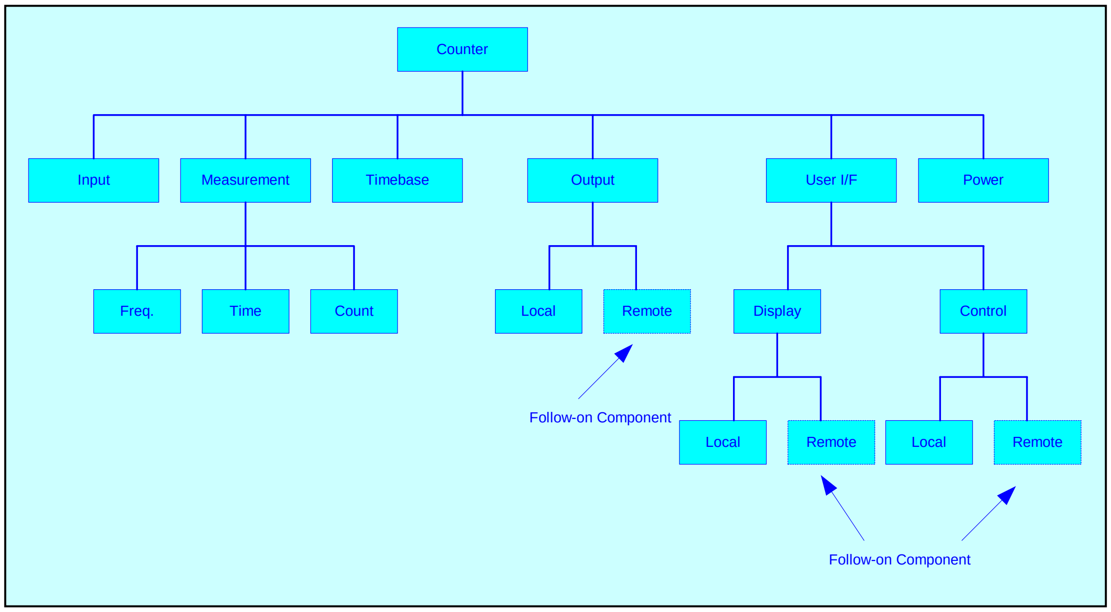
- The user,
- The factory,
- The future remote computer,
- The counter

The factory is an aggregation of test lines and numbers of navigation radios that must be tested. Note that we are using the looser term *aggregation* rather than *composition* here.

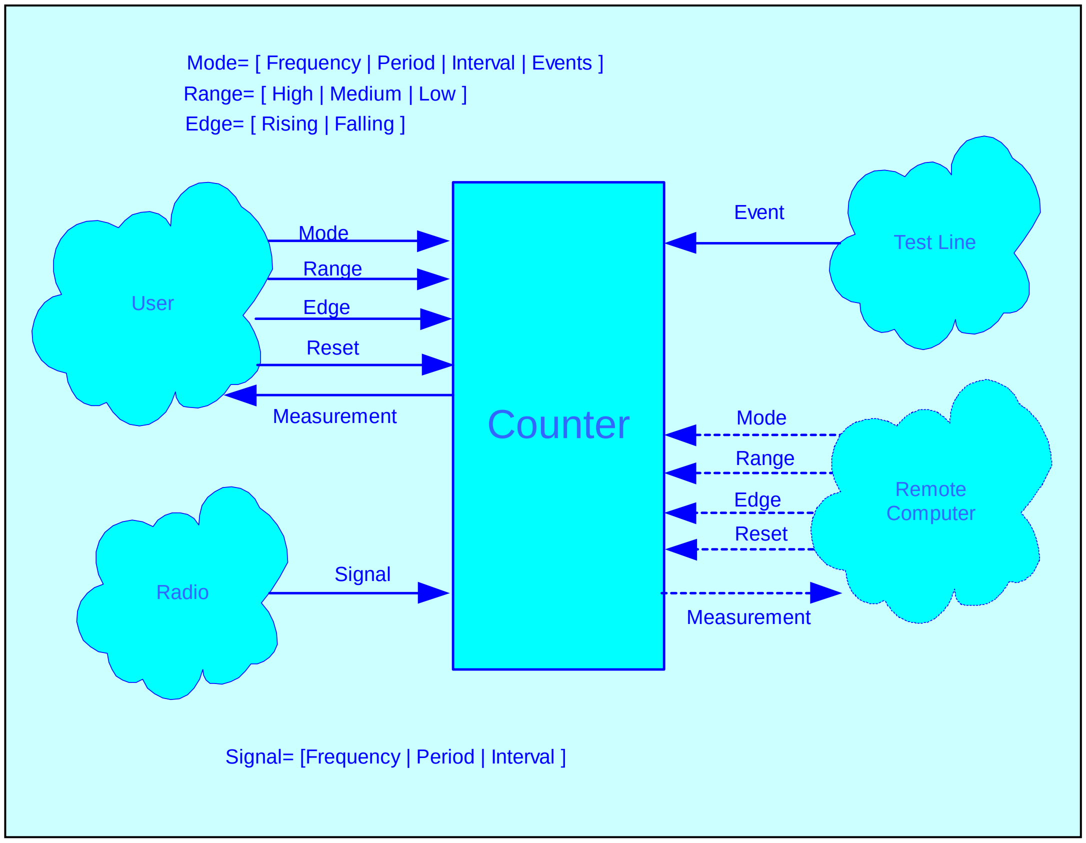
The design specification provided a high level block diagram of the system. For this problem, such a diagram provides good starting place for the initial hierarchical decomposition of the system. The following diagram elaborates on the counter component and gives one possible decomposition for that system.

The interface to the outside world is segregated into two functional blocks. The first is associated with the *presentation of information* to the user. The second is charged with *bringing in information* from the user and other tasks necessary to support the measurement. Both functional blocks are further decomposed into local operations versus remote operations.

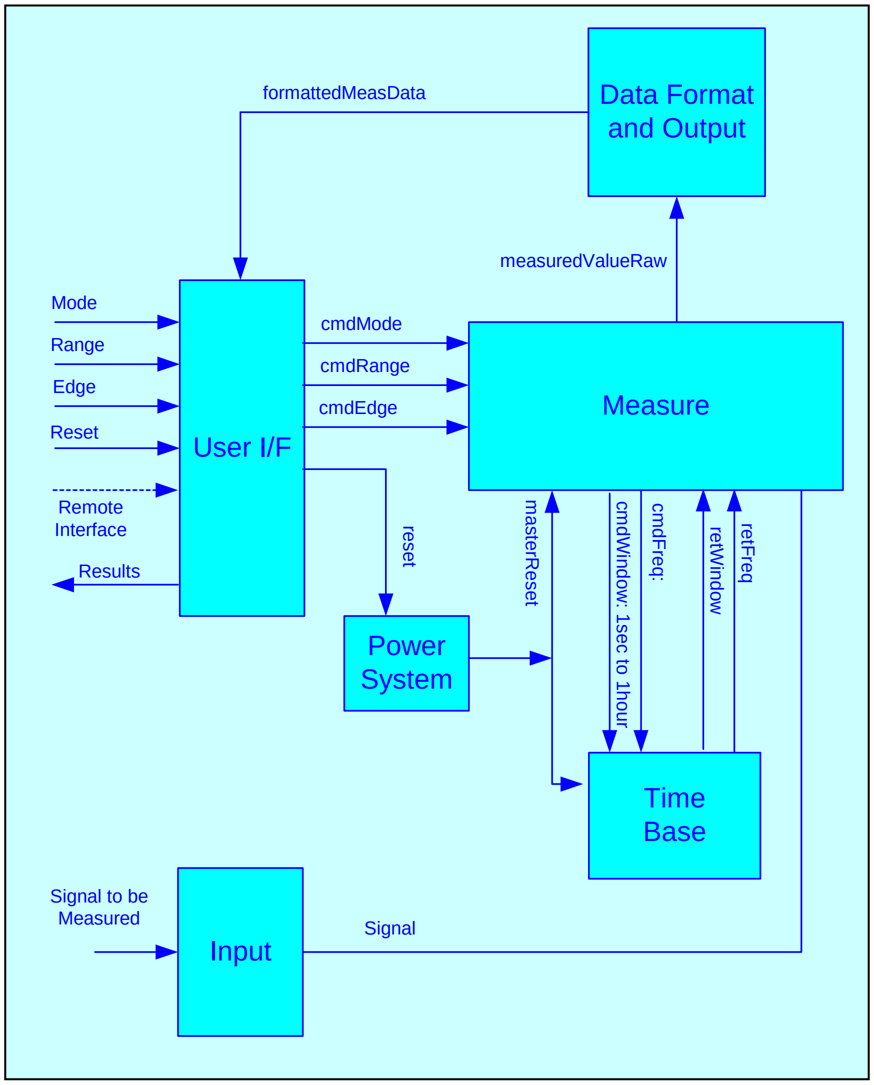
Such a choice is made in the first case because the display is considered to be an output function and control to be an input function. In the second case, two different sets of functionality and different grammars for expressing the user's commands are anticipated. Front panel operations tend to be rather straight forward; remote operations can be a bit more involved. Certainly, these are not the only choices.



The next drawing captures the interface between the counter and the surrounding environment.


Mode= [Frequency | Period | Interval | Events]
Range= [High | Medium | Low]
Edge= [Rising | Falling]
User
Mode
Range
Edge
Reset
Measurement
Counter
Event
Test Line
Mode
Range
Edge
Reset
Measurement
Remote Computer
Radio
Signal
Signal= [Frequency | Period | Interval]

The next drawing expresses a functional partitioning and the signal flow between the major functional blocks.



Next the system architecture is formulated and functions are then map onto the hardware and software blocks comprising that system.

12.11 Architectural Design

In executing an architectural design, the goal is to select the most appropriate solution to original problem based upon the exploration of variety of architectures and the choice of the best-suited hardware/software partitioning and allocation of functionality.

The view of a partition now changes to reflect a more detailed understanding of the system and involves the *mapping* or allocation of each functional module onto the appropriate physical hardware or software block(s). Such a mapping completely describes the hardware implementation of the system.

As noted earlier, one should always endeavor to broaden the scope of the architectural design so as not to preclude possible future enhancements. Certainly, this involves a balancing act between generality and practicality as well as simultaneously satisfying other specified requirements. Nonetheless, the plan should be for a system that evolves over its lifetime; if this is done well, add-ons, which are inevitable in today's systems, will be much easier.

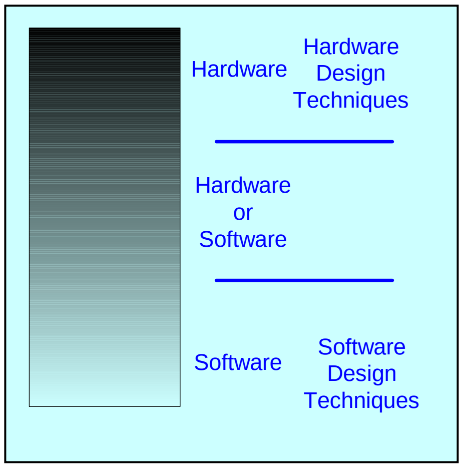
The major objective to the architectural design activity is the allocation or mapping of the different pieces of system functionality to the appropriate hardware and software blocks. Work is based upon the detailed functional structure. The performance requirements are analyzed and finally the constraints that are imposed by the available technologies as well as those that arise from the hardware and software specifications are taken into consideration.

The important constraints that must considered include such items as

- ✓ The geographical distribution,
- ✓ Physical and user interfaces,
- ✓ System performance specifications,
- ✓ Timing constraints and dependability requirements,
- ✓ Power consumption,
- ✓ Legacy components and cost.

Such constraints are strong factors for deciding which portions of the system should be implemented in software and which portions should be done in hardware.

The proper allocation of the pieces of functionality is generally obvious for a significant part of the system. For those, it's easy say, 'this part must be hardware or this part must be software.' The power supply, display, communications port, and the package containing the system are necessarily hardware. The operating system and associated drivers, it's generally agreed, are necessarily software.



The situation is expressed graphically as in the accompanying diagram. There is a gray area between the hardware and software where the implementation approach not precisely defined. In selecting the components that make up this area one is making engineering decisions or trade-offs of speed, cost, size, weight, as well as many other factors.

The *mapping* onto such an architecture completely defines the hardware implementation of the system. The hardware portion of the system is specified by a physical architecture that may comprise one or more microprocessors, complex logical devices or array logics, or/and custom integrated circuits. It's important to keep in mind that with today's systems, these microprocessors and microcontrollers can take on a variety of personalities: (CISC) complex instruction set, (RISC) reduced instruction set, or (DSP) digital signal processing core.

For most applications, a substantial portion of the software can be easily separated from the hardware and thereby permit its concurrent development. The remaining part, that in the boundary, is more difficult to partition and falls under what is called *co-design*.

12.11.1 Hardware and Software Specification and Design

The system specification gives a detailed quantification of the system's inputs, outputs, and functional behavior based upon our original requirements. The functional decomposition is analogous to those steps taken in defining the requirements. As the architecture of the design now begins to take shape, the objective is to determine, as fully as possible, the specifications for each of the physical components in the system and the interfaces between them. The specification of the hardware for the entire system is decided by defining the hardware architecture and all its properties. The specification of the software is obtained by defining the software implementation or block diagram (using any of a variety of methods) for each software component of the architecture.

Each functional subset to be implemented in software is described by a detailed software specification that expresses the priority of each task and the spatial (data coupling), and temporal dependence relations between tasks. UML diagrams including detailed state charts, timing diagrams, sequence diagrams, activity diagrams, and collaboration diagrams can all be very useful at this stage in the design.

A software implementation may or may not use a real-time kernel. With an off the shelf real-time kernel, the development time is reduced, but not the factory cost or time based performance specifications. For systems that don't use a real-time kernel (which represents 80% to 90% of small and medium systems) one can achieve a better optimization of the design when addressing high speed hard real-time constraints. Under such circumstances, the solution is being hand tailored to the specific problem rather than adapting a general purpose solution to a specific case.

For the software design, the following must be analyzed and decided:

- Whether to use a real-time kernel or not.
- Can several functions be combined in order to reduce the number of software tasks? If so, how?
- A priority for each task.
- An implementation technique for each inter-task relationship.

When it is appropriate, a real-time kernel or the services of an operating system can be used. In general, the main objective is to reduce the complexity of the organizational part in order to reduce the size and complexity of the software and the resulting development, testing, and debugging times.

Under such circumstances, a frequent choice is the *Rate Monotonic Scheduling* policy (this will be discussed shortly … more frequently executed tasks are assigned a higher priorities). Permanent functions (those that run continuously without an activating event) and some cyclic functions without timing constraints are usually implemented within a background task.

For the implementation of inter-task relationships, it is desirable to use procedure calls as much as possible thereby simplifying the organizational part and reducing the inter-task overhead. Such an implementation is only possible between functions with increasing relative priorities. Tasks triggered by hardware events are invoked through the processor interrupt or polling systems.

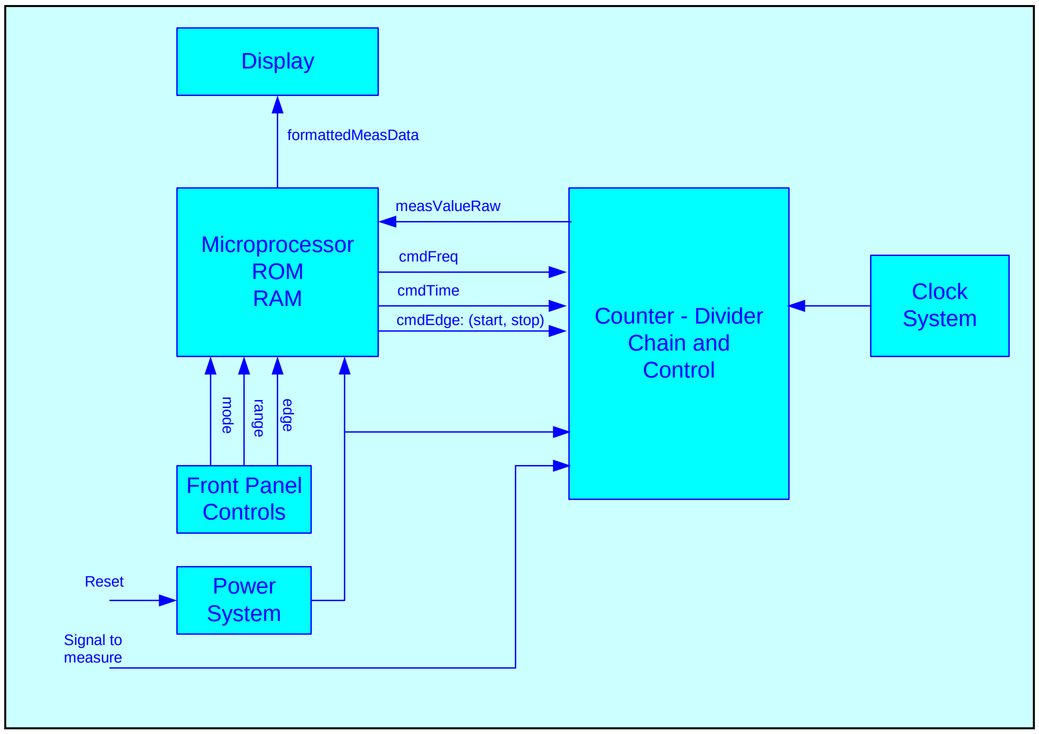
For each specific sub-part of the system in which the partition is not obvious, a detailed specification is written; the final hardware/software partition is determined through a process of successive refinements as was done in the earlier decomposition process. Each hardware/software partition must also include the hardware interfaces and the software drivers to support any inter-component communication.

The result is a complete mapping of all remaining functions and functional relations onto the hardware architecture. Among the important criteria that we strive to optimize are:

- Implementation (or factory) cost,
- Development time and cost,
- Performance and dependability constraints,
- Power consumption,
- Size

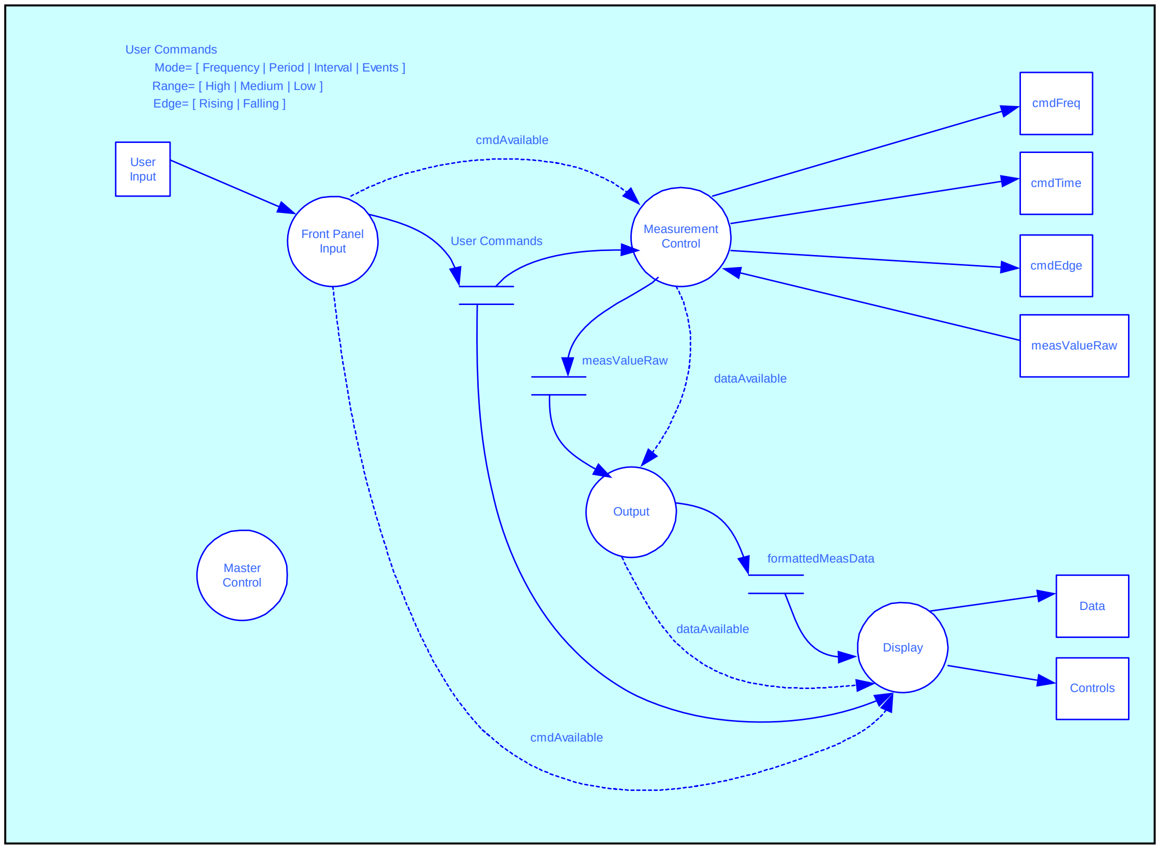
Example Continued…

The next step in developing the counter begins with formulating the hardware architecture; the software architecture follows. We then map each of the functions identified earlier onto the architecture. The following diagram presents the hardware components.



In the design, the microprocessor, the display, the front panel controls, and the power system are clearly hardware. In theory, the clock system as well as the counter-divider chain and associated control could be implemented in software. However, the frequency at which the counter is intended to operate (200 MHz) biases the decision towards a hardware solution.

The following diagram identifies the major software tasks, shared data, and I/O in a data and control flow diagram. The *front panel task* is continually checking (directly by polling or indirectly by interrupt) the state of the front panel for user input. A change in input is captured and passed to the *display task* (which will update the display accordingly) and to the *measurement task*. The *measurement task* issues the appropriate commands to the external *counter-divider chain control* block. At the end of each measurement, the raw data is read from the counter-divider and passed to the *output task*.



The *output task* properly formats the data and sends it to the *display task* for display on the front panel. The *master control task* manages the scheduling of all tasks and performs any necessary housekeeping or other duties as necessary.

12.12 Functional Model versus Architectural Model

A good question that one might ask at this stage is, 'Why is it necessary to design a functional model and an architectural model?' We start by looking at any system - hardware, software, a mix, it doesn't matter. It quickly becomes evident that the internal organization of a system is based on a collection of components and interconnections between them. An appropriate model has to include elements both at *functional* level and at the *architectural* level to be able to represent and evaluate hardware/software systems.

12.12.1 The Functional Model

The functional model describes a system through a *set of interacting functional elements*. The design proceeds at a high level without initial bias towards any specific implementation. We have the freedom to explore and to be creative. The behavior of a functional element is best described with a hierarchical and graphical model. The functional modules will interact using one of the following three types of relations:

- The *shared variable* relation - Which defines a data exchange without temporal dependencies.
- The *synchronization* relation - Which specifies temporal dependency.
- The *message transfer* by port - Which implies a producer/consumer kind of relationship.

We will discuss each of these when we study processes and inter process communication. All of them are critical in the design and development of today's embedded systems.

12.12.2 The Architectural Model

The architectural model describes the *physical* architecture of the system based on real components such as microprocessors, arrayed logics, special purpose processors, analog and digital components, and the many interconnections between them.

12.12.3 The Need for Both Models

These two views, when considered separately, are not sufficient to completely describe the design of contemporary systems. It is necessary to add the *mapping* between the *functional* viewpoint and the *architectural* one. Such a mapping defines a (functional) partition and the allocation of functional components to the hardware elements. This is also called *architectural configuration*.

The *functional model,* located between specification model and the architectural model, is suitable for representing the internal organization of a system. It explains all necessary functions and the couplings between them - expressed from the point of view of the original problem. Using such a scheme leads to a technology-independent solution. In particular with this kind of model, all or part of the description can be implemented either in software or hardware.

The functional model is the basis for a coarse-grain partitioning of the system. Such a partitioning leads naturally to the selection of which functions to implement in hardware or software. The *architectural structure* is finer grained and generally follows from the functional model; the architecture may also be imposed a priori.

12.13 Prototyping

The prototype phase leads to an operational system prototype. A prototype implementation includes:

- Detailed Design
- Debugging
- Validation
- Testing

Prototyping is naturally a bottom-up process since it consists of assembling individual parts and fleshing out more and more of the abstract functionalities. Each level of the implementation must be validated. That is, it must be checked for compliance with the specifications on the corresponding level in the top-down design.

Hardware and software implementations can be developed simultaneously and involve specialists in both domains, hopefully reducing the total implementation time. Often this doesn’t happen in reality. Typically, the software leads hardware. None-the-less, a complete solution can be generated and/or synthesized both for hardware (in the form of ASICs and standard cores etc.) and software (in the form of hardware / software interfaces). The resulting prototype can then be verified.

12.13.1 Implementation

Activities in this step are highly dependent on the technology used. Remember, the prototype is tool for understanding and confirming system design. It is a proof of concept. A word of caution, don't rush the analysis or design to get to the prototype. Also, don't be afraid to throw the prototype away. For small projects, it sometimes works to try to transform the prototype into the final product. For large projects, it's usually more of a proof-of-concept that almost never can be migrated.

Remember, those who hurry through the design and coding because there's a lot of testing to do are going to be spending long nights getting things to work and even longer nights with unhappy customers. For some reason, customers don't seem to have much of a sense of humor when the failure of a product they have purchased has just cost them several million dollars. If you’re selling to a general market, *your company* has just lost several million in R&D costs and you still don’t have a product to take to market. So now, it’s even worse, because you’ve missed an opportunity for sales revenue with a product that you can’t sell because it is poorly conceived, or it still isn’t ready.

12.13.2 Analyzing the System Design

We’ve been studying the system design process while moving from requirements to a design. Now that the first level design is in place, it must be critically analyzed. This step provides several important checks on the design, first, and foremost, it verifies that the solution meets the original requirements and specifications. At this stage in the design flow, it may also be necessary to trade-off different architectural and functional aspects of the design. Such trade-offs must be made according to criteria identified in the original specification.

The first step entails a static analysis of the system. At this stage, the architecture of the system is examined. Of immediate interest is *not* how the system will behave at run time. The major objectives are to have a system that is easy to understand, build, test, and maintain. All too often from new designers (and, unfortunately, some who should know better), have I heard the phrase, "…but it works!!!" For systems that we're proud to put our name on, getting it to work is only one very small part of the job. Moreover, it’s easy to make a one-off version of any system to work. Making one or ten million of the same design in production that will ultimately work safely and reliably is a much larger challenge.

The main goal in any design is to work ourselves out of a job. We want the design to be so reliable and so well documented that any future modifications and extensions are effortless. The caveat, of course, is that one must also know what sufficient reliability is and when to stop documenting. Well documented means just enough so that people can easily understand the design, but not so much that it becomes the primary deliverable.

12.13.2.1 Static Analysis

Static analysis should consider 3 areas:

1. Coupling

   We have examined this aspect of a design already. Coupling is related to number and complexities of the relationships that exist have amongst the various system modules. It also gives a measure a measure of implications of a change. The goal is loose coupling.

2. Cohesiveness

   Another issue that is worth re-stressing, cohesiveness is a measure of functional homogeneity of elements that comprise the modules. This applies to both the components and the relations. One must consider both external and internal views. External cohesion begins with the appropriate naming and meaning for elements. Internally, the structure and relationships among components is analyzed. For example, coupling through shared data is more cohesive than messages. Messages imply a temporal dependency.

3. Complexity

   Two kinds of complexity are identified: *functional* and *behavioral*. Functional complexity is characterized by:

   - The number of internal functions and relational components
     The goal is to keep these small. Generally, as the number of functions and relations decreases so does the complexity of the design. Note, this does not mean to sacrifice clarity.

   - Interconnections amongst elements comprising each module.
     The earlier discussion of coupling applies here as well. Keep things simple.

Behavioral complexity is characterized by

- The number of inputs and outputs

  Once again, the target is a smaller number.

- The length and ease of reading and understanding the description of the module.

  If several paragraphs or a page of written text (in sub 6 point font) are required to describe the function of one of the modules, that module is probably too complex. To simplify such descriptions, use tables, logical equations, or pseudo code.

- The flow control through the module and the number and structure of state variables.

  Have a single major thread of control through the module and keep the number of states small.

12.13.2.2 Dynamic Analysis

The objective in performing a dynamic analysis on the system is to determine how it will behave in a context that closely approximates the ultimate working environment. Dynamic analysis considers the following:

- Behavior Verification

  The goal is to ensure that the behavior of system, in its operating environment, meets the *operational* specification. That is, does it perform the functions it was intended to perform? This verification includes behavior at the boundaries of those functions. To be able to do so, of course, we need a good specification in the first place.

- Performance Analysis

  Performance Analysis ensures that the system, in its operating environment, meets the *performance* specification. The focus is on specific values for inputs and outputs. We'll talk about this in a later chapter.

- Trade-off Analysis

  A Trade-off Analysis is necessary to determine optimal solution for the given constraints and objectives. Such an analysis, based upon only small set of performance criteria, may affect the ultimate success or failure of the product.

12.14 Other Considerations

The two additional complementary and concurrent activities that need to be considered in today's business world are capitalization and reuse and requirements and traceability management. Let's look briefly at capitalization. Design reuse is one of the central threads in this text.

12.14.1 Capitalization and Reuse

Capitalization

Capitalization and reuse are activities that are essential to the contemporary design process. Proper and efficient exploitation of intellectual properties (IPs) is very important today. Intellectual properties are designs, often patented, that can be sold to another party to develop and sell as (a part of) their product. The company MIPS, for example, designs computer architectures. They don't actually do any implementation themselves, the design is their product.

Reuse

Any consideration of component reuse is an activity to be done during the functional and architectural design phases of the project. Note, one can sometimes consider these during prototyping as well.

One of the main purposes is to help designers shorten the development life cycle. Component reuse is facilitated in two ways: *present* and *future.* Reuse is supported in the present by identifying a set of external (existing) functional or architectural components that can satisfy some parts of desired functionality. Future reuse is supported by identifying components in the system under design that will be reusable in other projects or products.

To be reused, a component needs to be

- Well-defined
- Properly modularized
- Conform to some interchange standard

A well thought out, well designed module will be much easier to adapt to a new situation than one that someone pieced together for some ad hoc purpose and barely got working. The same is true for a portion of a well modularized system.

If, during the design phase, one makes decisions with an eye to modules that could be reused, the chances of such reuse are greatly enhanced. Finally, if the goal is for a module to have wider applicability than a local venue, then the designs must accommodate existing national and international standards. With today's international market growing daily, it is incumbent upon us design to such standards.

Once again, the real-world intrudes, and trade-offs are part of the process. While designing for reusability or striving for a modular design, there are other factors to be considered. Suppose there isn't enough ROM space for the code if it's designed to be completely modular, the may be modified to be very application specific. While it's known that the decision might create problems in the future, we'll end up with a non-competitive product if the budget is exceeded.

12.14.2 Requirements Traceability and Management

Requirements Management

Requirements traceability refers to the ability to follow the life of a requirement (from the original specification) in both the forward and reverse directions through the entire design process and the design. It should be clear that traceability is potentially a one-to-many relationship between a requirement and the components it relates or traces to (or that implement it). An accurate and complete record of traceability between requirements and system components provides several important pieces of information through the product life cycle. Among these are included,

- The means for the project manager (potentially) the customer to monitor the development progress.
- A path that can be used during the verification and validation of the product against the original specification. Knowing where and how a specified requirement has been implemented facilitates confirming that the requirement has been faithfully implemented.
- A means of identifying which hardware or software modules are affected if a requirement changes.

Requirements Management

Requirements management addresses

- Requirement modifications
- Changes
- Improvements
- Corrections

During the design, such changes are difficult to avoid for many reasons. Therefore a clear procedure that facilitates a way to accommodate such modifications has to be used during the whole design process.

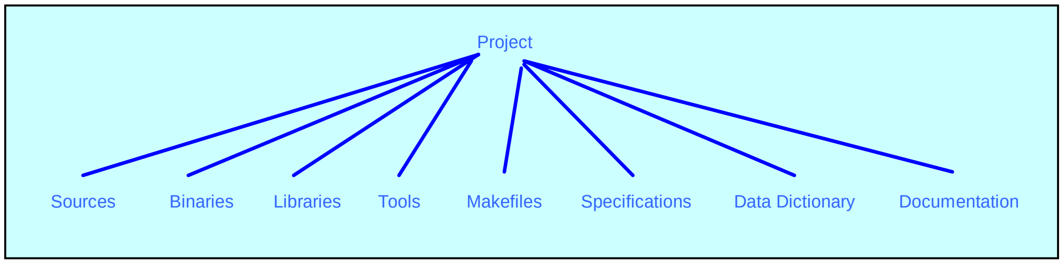
12.15 Archiving the Project

When the product has finally been released to production, there is some work that remains to be done. During development, a tremendous amount of important design information has been produced. Most of that information must be retained for a variety of reasons. If the product follows the typical life cycle, bugs that must be fixed will be discovered as customers use the product, there will be future revisions, new features will be expected and added, the next generation product will build on the current to name just a few. The obvious question is what must be saved?

The problem of dealing with what to archive is no different from confronting the original design. That said, we use the same approach and start at the top. The typical project will have had many contributors. A basic list can include,

- Product Planning
- Design and Development
- Test
- Manufacturing
- Marketing
- Sales

Each group will have information, knowledge, documentation, tools that will be important in future. Let's focus on the technical subset of these: design and development, test, and manufacturing. In earlier studies of safe and robust design, we identified a typical software project directory structure. That diagram is presented here for reference.



Each of the groups participating in the development should have a similar directory documenting their portion of the project. The project directories and all their contents are one of the main items that must be archived. These are obvious.

Now, the less obvious. Today, software, firmware, *and* software tools are essential to the design and development of any embedded system. If the source code it is lost or the ability to rebuild from sources is lost, any future work on the project will be seriously impaired. Today, source code no longer means just the C, C++, Java, or assembler listing in electronic form or on magnetic media.

In previous years, hardware was generally supported by hand drawn hard copy documentation. If a drawing was lost, it could be regenerated by skilled designers by reverse engineering the existing part. Today a rich set of CAD (computer aided design), CAM (computer aided manufacturing), and IC and FPGA modeling and synthesis tools have supplanted the old methods.

All of those tools run on a computer. All of those tools are routinely modified or updated by their vendor. All of those tools also have a product life cycle and ultimately will no longer be supported. If the archived tools will not execute on today's computer running today's operating system, they are of little use. Today, in addition to archiving the end product, archiving the complete development environment – computer, hard drive, operating system, etc. – is well worth considering. The documentation for the tools should be included in that list as well.

An essential step once the collected archive has been set is to conduct what is called a *virgin build*. A virgin build begins with a completely new environment or context. Next, the archived tools are installed and set up. The tools are run, as appropriate, and tested to see if the designated components of the product can be recreated. If the process fails, the missing components must be identified, added to the archive, and the process repeated.

Too often, over the span of the product development we build simple special purpose tools to help manage the tasks of developing and building the system then forget that they're an essential part of the build or synthesis when creating the archive. The virgin build quickly reveals when those tools are missing.

Today, the financial investment in all aspects of a project development is significant. Retaining and protecting that investment for future use is an important closure to the cycle.

12.16 Summary

In this chapter, we have introduced and studied the major phases of the development process for embedded systems. The more detailed aspects of that process are covered in conjunction with the study of the design and test of the specific hardware and software elements of the system.

We've see that design is process of translating customer requirements into working system. We've learned the complexity of contemporary systems now demands a more formal approach and more formal methods. Following a formal specification, we look at ways of partitioning the system as a step in developing a functional design. We formulate a functional model then develop and refine the model. Eventually we map our functional model on to the architectural structure. We conclude with a working prototype, meanwhile, analyzing the system design both during and after development.

We have looked at several other important considerations in the design lifecycle. These include intellectual property, component/module reuse, and requirements management and the archival process.