Chapter 2

Structure of Complex Systems

2.1 SYSTEM BUILDING BLOCKS AND INTERFACES

The need for a systems engineer to attain a broad knowledge of the several interacting disciplines involved in the development of a complex system raises the question of how deep that understanding needs to be. Clearly, it cannot be as deep as the knowledge possessed by the specialists in these areas. Yet it must be sufficient to recognize such factors as program risks, technological performance limits, and interfacing requirements, and to make trade-off analyses among design alternatives.

Obviously the answers depend on specific cases. However, it is possible to provide an important insight by examining the structural hierarchy of modern systems. Such an examination reveals the existence of identifiable types of the building blocks that make up the large majority of systems and represent the lower working level of technical understanding that the systems engineer must have in order to do the job. This is the level at which technical trade-offs affecting system capabilities must be worked out and at which interface conflicts must be resolved in order to achieve a balanced design across the entire system. The nature of these building blocks in their context as fundamental system elements and their interfaces and interactions are discussed in the ensuing sections.

2.2 HIERARCHY OF COMPLEX SYSTEMS

In order to understand the scope of systems engineering and what a systems engineer must learn to carry out the responsibilities involved in guiding the engineering of a complex system, it is necessary to define the general scope and structure of that system. Yet, the definition of a ''system'' is inherently

applicable to different levels of aggregation of complex interacting elements. For example, a telephone substation, with its distributed lines to the area that it serves, can be properly called a "system." Hotel and office building switchboards, with their local lines, may be called "subsystems," and the telephone instruments may be called "components" of the system. At the same time, the substation may be regarded as a subsystem of the city telephone system, and that, in turn, to be a subsystem of the national telephone system.

In another example, a commercial airliner certainly qualifies to be called a "system," with its airframe, engines, controls, and so on, being subsystems. The airliner may also be called a subsystem of the air transportation system, which consists of the air terminal, air-traffic control, and other elements of the infrastructure in which the airliner operates. Thus, it is often said that every system is a subsystem of a higher-level system, and every subsystem may itself be regarded as a system.

The above relationships have given rise to terms such as "super-systems" to refer to overarching systems like the wide-area telephone system and the air transportation system. In networked military systems, the term "system of systems" has been coined to describe integrated distributed sensor and weapon systems such as those in a modern navy task force.

Model of a Complex System

While learning the fundamentals of systems engineering, this ambiguity of the scope of a "system" may be confusing to some students. Therefore, for the purpose of illustrating the typical scope of a systems engineer's responsibilities, it is useful to create a more specific model of a typical system. As will be described later, the technique of modeling is one of the basic tools of systems engineering, especially in circumstances where unambiguous and quantitative facts are not readily available. In the present instance, this technique will be used to construct a model of a typical complex system in terms of its constituent parts. The purpose of this model is to define a relatively simple and readily understood system architecture, which can serve as a point of reference for discussing the process of developing a new system and the role of systems engineering throughout the process. While the scope of this model does not extend to that of "super-systems" or "system of systems," it is representative of the majority of systems that are developed by an integrated acquisition process, such as a new aircraft, weapon system, or terminal air traffic control system.

By their nature, complex systems have a hierarchical structure in that they consist of a number of major interacting elements, generally called **subsystems**, which themselves are composed of more simple functional entities, and so on down to primitive elements such as gears, transformers, or light bulbs, usually referred to as **parts**. Commonly used terminology for the various architectural levels in the structure of systems is confined to the generic system and **subsystem** designation for the uppermost levels and parts for the lowest.

For reasons that will become evident later in this section, the system model as defined in this book will utilize two additional intermediate levels, which will be called **components** and **subcomponents**. While some models use one or two more intermediate levels in their representation of systems, these five have proven to be sufficient for the intended purpose.

Definition of System Levels Figure 2-1 illustrates the above characterization of the hierarchical structure of the system model. In this diagram various types of systems are listed horizontally, and successive levels of subdivisions within each system are arranged vertically. Representative types of complex systems employing advanced technology are identified at the top of the diagram while the smallest system subdivision, **parts**, is listed at the bottom.

In describing the various levels in the system hierarchy depicted in the figure, it was noted previously that the term **system** as commonly used does not correspond to a specific level of aggregation or complexity, it being understood that systems may serve as parts of more complex aggregates or super-systems, and subsystems may themselves be thought of as systems. For the purpose of the ensuing discussion, this ambiguity will be avoided by limiting the use of the term system to those entities that:

1. Possess the properties of an engineered system, as defined in Chapter 2, and
2. Perform a significant useful service with only the aid of human operators and standard infrastructures (e.g., power grid, highways, fueling stations, communication lines, etc.). According to the above conditions, a

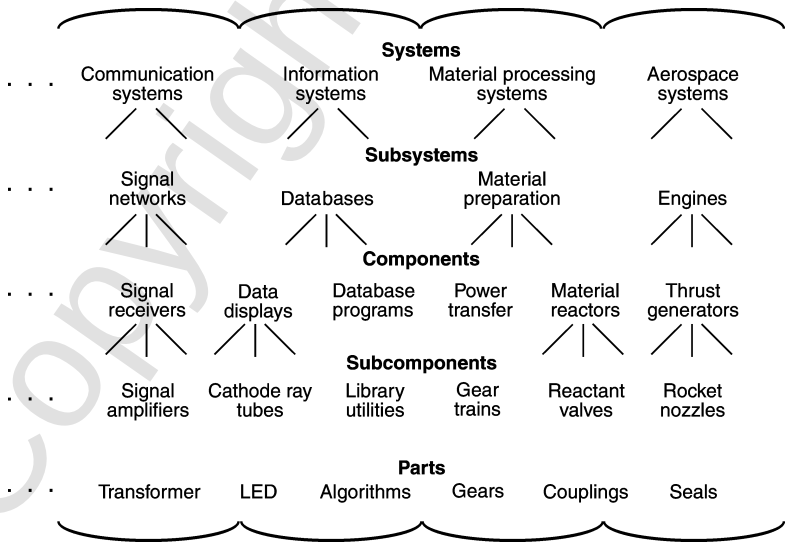

Fig. 2-1 System design hierarchy.

passenger aircraft would fit the definition of a system, as would a personal computer with its normal peripherals of input and output—keyboard, display, and so on.

The first subordinate level in the system hierarchy defined in Figure 2-1 is appropriately called a **subsystem**, and has the conventional connotation of being a major portion of the system that performs a closely related subset of the overall system functions. Each subsystem may in itself be quite complex, having many of the properties of a system except the ability to perform a useful function in the absence of its companion subsystems. Each subsystem typically involves several technical disciplines (e.g., electronic, mechanical, etc.).

The term **component** is commonly used to refer to a range of mostly lower level entities, but in this book, the term **component** will be reserved to refer to the middle level of system elements described above. Components will often be found to correspond to configuration items (CIs) in government system acquisition notation.

The level below the component building blocks is comprised of entities, referred to as **subcomponents**, that perform elementary functions and are composed of several parts. The lowest level, comprised of **parts**, represents elements that perform no significant function except in combination with other parts. The great majority of parts come in standard sizes and types, and can usually be obtained commercially.

Domains of the Systems Engineer and Design Specialist

From the above discussion, the hierarchical structure of engineered systems can be used to define the respective knowledge domains of both the systems engineer and the design specialist. The intermediate system **components** occupy a central position in the system development process, representing elements that are, for the most part, products fitting within the domain of industrial design specialists, who can adapt them to a particular application based on a given set of specifications. The proper specification of components, especially to define performance and ensure compatible interfaces, is the particular task of systems engineering. This means that the systems engineer's knowledge must extend to the understanding of the key characteristics of components from which the system may be constituted, largely through dialogue and interaction with the design specialists, so that he or she may select the most appropriate types, and specify their performance and interfaces with other components.

The respective knowledge domains of the systems engineer and design specialist are shown in Figure 2-2, which is an overlay of the system hierarchy depicted in Figure 2-1. It shows that the systems engineer's knowledge needs to extend from the highest level, the system and its environment, down through the middle level of primary system building blocks or **components**. At the same time, the design specialist's knowledge needs to extend from the lowest

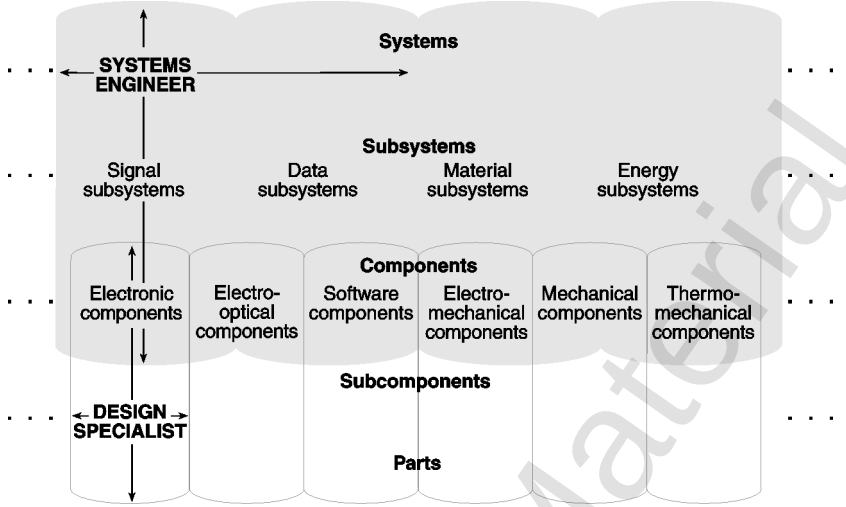

Fig. 2-2 Knowledge domains of systems engineer and design specialist.

level of parts, up through the components level, at which point their two knowledge domains "overlap." This is the level at which the systems engineer and the design specialist must communicate effectively, identify and discuss technical problems, and negotiate workable solutions that will not jeopardize either the system design process or the capabilities of the system as a whole.

The horizontal boundaries of these domains are deliberately shown as wavy lines in the figure, to indicate that they should be extended as necessary to reflect the composition of the particular system. When a subcomponent or part happens to be critical to the system's operation (e.g., the ill-fated seal in the space shuttle *Challenger*'s booster rocket) the systems engineer should be prepared to learn enough about its behavior to identify its potential impact on the system as a whole. This is frequently the case in high performance mechanical and thermo-mechanical devices, such as turbines and compressors. Conversely, when the specified function of a particular component imposes unusual demands on its design, the design specialist should call on the systems engineer to reexamine the system-level assumptions underlying this particular requirement.

2.3 SYSTEM BUILDING BLOCKS

An important and generally unrecognized finding resulting from an examination of the hierarchical structure of a large variety of systems is the existence of an intermediate level of elements of types that recur in a variety of systems. Devices such as signal receivers, data displays, torque generators, containers,

and numerous others perform significant functions used in many systems. Such elements typically constitute product lines of commercial organizations, which may configure them for the open market or customize them to specifications to fit a complex system. In Figure 2-1 the above elements are situated at the third or middle level, and are referred to by the generic name **component**.

The existence of a distinctive set of middle-level system building blocks can be seen as a natural result of the conditions discussed in Chapter 1 for the origin of complex systems, namely (1) advancing technology, (2) competition, and (3) specialization. Technological advances are generally made at basic levels, such as the development of semiconductors, composite materials, light emitting devices, graphic user interfaces, and so on. The fact of specialization tends to apply such advances primarily to devices that can be designed and manufactured by people and organizations specialized in certain types of products. Competition, which drives technology advances, also favors specialization in a variety of specific product lines. A predictable result is the proliferation of advanced and versatile products that can find a large market (and hence achieve a low cost) in a variety of system applications. The current emphasis in defense system development on adapting COTS (commercial off-the-shelf) components, wherever practicable, attempts to capitalize on economies of scale found in the commercial component market.

Referring back to Figure 2-1, it is noted that as one moves up through the hierarchy of system element levels, the functions performed by those in the middle or **component** level are the first that provide a significant functional capability, as well as being found in a variety of different systems. For this reason, the types of elements identified as **components** in the figure were identified as basic system building blocks. Effective systems engineering therefore requires a fundamental understanding of both the functional and physical attributes of these ubiquitous system constituents. To provide a framework for gaining an elementary knowledge base of system building blocks, a set of models has been defined to represent commonly occurring system components. This section is devoted to the derivation, classification, interrelationships, and common examples of the defined system building blocks.

Functional Building Blocks: Functional Elements

The three basic entities that constitute the media on which systems operate are:

Information: the content of all knowledge and communication
Material: the substance of all physical objects
Energy: which energizes the operation and movement of all active system components.

Because all system functions involve a purposeful alteration in some characteristic of one or more of these entities, the latter constitute a natural basis for classifying the principal system functional units. Since information elements

are more than twice as populous as the material and energy entities among system functions, it is convenient to subdivide them into two classes: (1) elements dealing with propagating information (e.g., radio signals), to be referred to as **signal elements**, and (2) those dealing with stationary information (e.g., computer programs), to be referred to as **data elements**. The former class is primarily associated with sensing and communications and the latter with analysis and decision processes. This results in a total of four classes of system functional elements:

1. Signal elements: which sense and communicate information.
2. Data elements: which interpret, organize, and manipulate information.
3. Material elements, which provide structure and transformation of materials.
4. Energy elements, which provide energy and motive power.

To provide a context for acquainting the student with significant design knowledge peculiar to each of the four broad classes of functions, a set of generic functional elements have been defined that represent the majority of important types for each class.

To make the selected elements self-consistent and representative, three criteria may be used to ensure that each element is neither trivially simple nor inordinately complex, and has wide application:

1. **Significance**: Each functional element must perform a distinct and significant function, typically involving several elementary functions.
2. **Singularity**: Each functional element should fall largely within the technical scope of a single engineering discipline.
3. **Commonality**: The function performed by each element can be found in a wide variety of system types.

In configuring the individual functional elements, it is noted that regardless of their primary function and classification, their physical embodiments are necessarily built of material, usually controlled by external information, and powered by electricity or some other source of energy. Thus, a television set, whose main function is to process information in the form of a radio frequency signal into information in the form of a TV picture and sound, is built of materials, powered by electricity, and controlled by user-generated information inputs. Accordingly, it should be expected that most elements in all classes would have information and energy inputs in addition to their principal processing inputs and outputs.

The above process converges on a set of 23 functional elements, five or six in each class. These are listed in the middle column of Table 2-1. The function of the class as a whole is shown in the left column, and typical applications that might embody the individual elements are listed in the right column. It should be noted that the above classification is not meant to be absolute, but is estab-

TABLE 2-1 System Functional Elements

Class Function	Element Function	Application
Signal—generate, transmit, distribute, and receive signals used in passive or active sensing and in communications	Input signal	TV camera
	Transmit signal	FM radio transmitter
	Transduce signal	Radar antenna
	Receive signal	Radio receiver
	Process signal	Image processor
	Output signal	TV tube
Data—analyze, interpret, organize, query, and/or convert information into forms desired by the user or other systems	Input data	Keyboard
	Process data	Computer CPU
	Control system	Operating system
	Control processing	Word processor
	Store data	Magnetic disk
	Output data	Printer
Material—provide system structural support or enclosure, or transform the shape, composition, or location of material substances	Support material	Airframe
	Store material	Shipping container
	React material	Autoclave
	Form material	Milling machine
	Join material	Welding machine
	Control position	Servo actuator
Energy—provide energy or propulsive power to the system	Generate thrust	Turbojet engine
	Generate torque	Reciprocating engine
	Generate electricity	Solar cell array
	Control temperature	Refrigerator
	Control motion	Auto transmission

lished solely to provide a systematic and logical framework for discussing the properties of systems at the levels of importance to systems engineers.

Fundamentally, the functional design of any system may be defined by conceptually combining and interconnecting the identified functional elements—along with perhaps one or two very specialized elements that might perform a unique function in certain system applications—so as to logically derive the desired system capabilities from the available system inputs. In effect the system inputs are transformed and processed through the interconnected functions to provide the desired system outputs.

Physical Building Blocks: Components

System physical building blocks are the physical embodiments of the functional elements, consisting of hardware and software. Consequently they have the same distinguishing characteristics of significance, singularity, and commonality, and are at the same level in the system hierarchy, generally one level

below a typical subsystem, and two levels above a part. They will be referred to as **component elements** or simply as **components**.

The classes into which the component building blocks have been categorized are based on the different design disciplines and technologies that they represent. In total, 31 different component types were identified and grouped into six categories, as shown in Table 2-2. The table lists the category, component name, and the functional element(s) with which it is associated. As in the case of functional elements, the component names are indicative of

TABLE 2-2 Component Design Elements

Category	Component	Functional Element(s)
Electronic	Receiver	Receive signal
	Transmitter	Transmit signal
	Data processor	Process data
	Signal processor	Process signal
	Communication processors	Process signal/data
	Special electronic component	Various
Electro-optical	Optical sensing device	Input signal
	Optical storage device	Store data
	Display device	Output signal/data
	High energy optics device	Form material
	Optical power generator	Generate electricity
Electromechanical	Inertial instrument	Input data
	Electric generator	Generate electricity
	Data storage device	Store data
	Transducer	Transduce signal
	Data input/output device	Input/Output data
Mechanical	Framework	Support material
	Container	Store material
	Material processing machine	Form/Join material
	Material reactor	React material
	Power transfer device	Control motion
Thermomechanical	Rotary engine	Generate torque
	Jet engine	Generate thrust
	Heating unit	Control temperature
	Cooling unit	Control temperature
	Special energy source	Generate electricity
Software	Operating system	Control system
	Application program	Control processing
	Support software	Control processing
	Firmware	Control system

their primary function, but in this case represent things rather than processes. Many of these represent devices in widespread use.

The systems engineer's concern with the implementation of the functional elements into components is related to a different set of factors than those associated with the initial functional design itself. Here the predominant issues are reliability, form and fit, compatibility with the operational environment, maintainability, producibility, testability, safety, and cost, along with the requirement that product design does not violate the integrity of the functional design. The depth of the systems engineer's understanding of the design of individual components needs to extend to the place where the system-level significance of these factors may be understood, and any risks, conflicts, and other potential problems addressed.

The required extent and nature of such knowledge varies widely according to the type of system and its constitution. A systems engineer dealing with an information system can expect to concentrate largely on the details of the software and user aspects of the system, while considering mainly the external aspects of the hardware components, which are usually standard (always paying special attention to component interfaces). At another extreme, an aerospace system such as a missile consists of a complex and typically nonstandard assemblage of hardware and software operating in a highly dynamic and often adverse environment. Accordingly, an aerospace systems engineer needs to be knowledgeable about the design of system components to a considerably more detailed level so as to be aware of the potentially critical design features before they create reliability, producibility, or other problems during the product engineering, test, and operational stages.

Applications of System Building Blocks

The system building block model described above may be useful in several ways:

1. The categorization of functional elements into the four classes of signal, data, material, and energy elements can help suggest what kind of actions may be appropriate to achieve required operational outcomes.
2. Identifying the classes of functions that need to be performed by the system may help group the appropriate functional elements into subsystems, and thus facilitate functional partitioning and definition.
3. Identifying the individual functional building blocks may help define the nature of the interfaces within and between subsystems.
4. The interrelation between the functional elements and the corresponding one or more physical implementations can help visualize the physical architecture of the system.
5. The commonly occurring examples of the system building blocks may suggest the kinds of technology appropriate to their implementation, including possible alternatives.

6. For those specialized in software and unfamiliar with hardware technology, the relatively simple framework of four classes of functional elements and six classes of physical components should provide an easily understood organization of hardware domain knowledge.

2.4 THE SYSTEM ENVIRONMENT

The system environment may be broadly defined as everything outside of the system that interacts with the system. The interactions of the system with its environment form the main substance of system requirements. Accordingly, it is important at the outset of system development to identify and specify in detail all of the ways in which the system and its environment interact. It is the particular responsibility of the systems engineer to understand not only what these interactions are, but also their physical basis, to make sure that the system requirements accurately reflect the full range of operating conditions.

System Boundaries

To identify the environment in which a new system operates, it is necessary to identify the system's boundaries precisely, that is, to define what is inside the system and what is outside. Since we are treating systems engineering in the context of a system development project, the totality of the system will be taken as that of the product to be developed.

This definition may seem to contradict the conventional concept of a system. For example, most systems cannot operate without the active participation of human operators exercising decision and control functions. In a functional sense, the operators may well be considered to be integral parts of the system. However, to the systems engineer, the operators constitute elements of the system environment, and impose interface requirements that the system must be engineered to accommodate. Accordingly, in our definition, the operators will be considered to be external to the system.

As noted earlier, many, if not most, complex systems can be considered as parts of larger systems. An automobile operates on a network of roads, and is supported by an infrastructure of service stations. However, these are not changed to suit a new automobile. A spacecraft must be launched from a complex gantry, which performs the fueling and flight preparation functions. The gantry, however, is usually part of the launch complex and not part of the spacecraft's development. In the same manner, the electrical power grid is a standard source of electricity, which a data processing system may utilize. Thus the super-systems identified in the above examples need not be considered in the engineering process as part of the system being developed, but as an essential element in its operational environment, and to the extent required to assure that all interfacing requirements are correctly and adequately defined.

Systems engineers must also become involved in interface decisions affecting designs of both their own and an interfacing system. In the example of a spacecraft launched from a gantry, some changes to the information handling and perhaps other functions of the gantry may well be required. In such instances the definition of common interfaces and any associated design issues would need to be worked out with engineers responsible for the launch complex.

Types of Environmental Interactions

To understand the nature of the interactions of a system with its surroundings, it is convenient to distinguish between primary and secondary interactions. The former involve elements that interact with the system's primary functions, that is, represent functional inputs, outputs, and controls; the latter relate to elements that interact with the system in an indirect nonfunctional manner, such as physical supports, ambient temperature, and so on. Thus, the functional interactions of a system with its environment include its inputs and outputs, and human control interfaces. Operational maintenance may be considered a quasi-functional interface. The physical environment includes support systems, system housing, and shipping, handling, and storage. Each of these is briefly described below.

Inputs and Outputs The primary purpose of most systems is to operate on external stimuli and/or materials in such a manner as to process these inputs in a useful way. For a passenger aircraft, the materials are the passengers, their luggage, and fuel, and the aircraft's function is to transport the passengers and their belongings to a distant destination rapidly, safely, and comfortably. Figure 2-3 illustrates some of the large variety of interactions that a complex system has with its operating environment for the case of a passenger aircraft.

System Operators As noted previously, virtually all systems, including automated systems, do not operate autonomously but are controlled to some degree by human operators in performing their function. For the purposes of defining the systems engineer's task the operator is part of the system's environment. The interface between the operator and the system (human–machine interface) is one of the most critical of all because of the intimate relationship between the control exercised by the operator and the performance of the system. It is also one of the most complex to define and test.

Operational Maintenance The requirements for system readiness and operational reliability relate directly to the manner in which it is to be maintained during its operating life. This requires that the system be designed to provide access for monitoring, testing, and repair—requirements that are frequently not obvious at the outset, but nevertheless must be addressed early in the development process. Thus, it is necessary to recognize and explicitly provide for the maintenance environment.

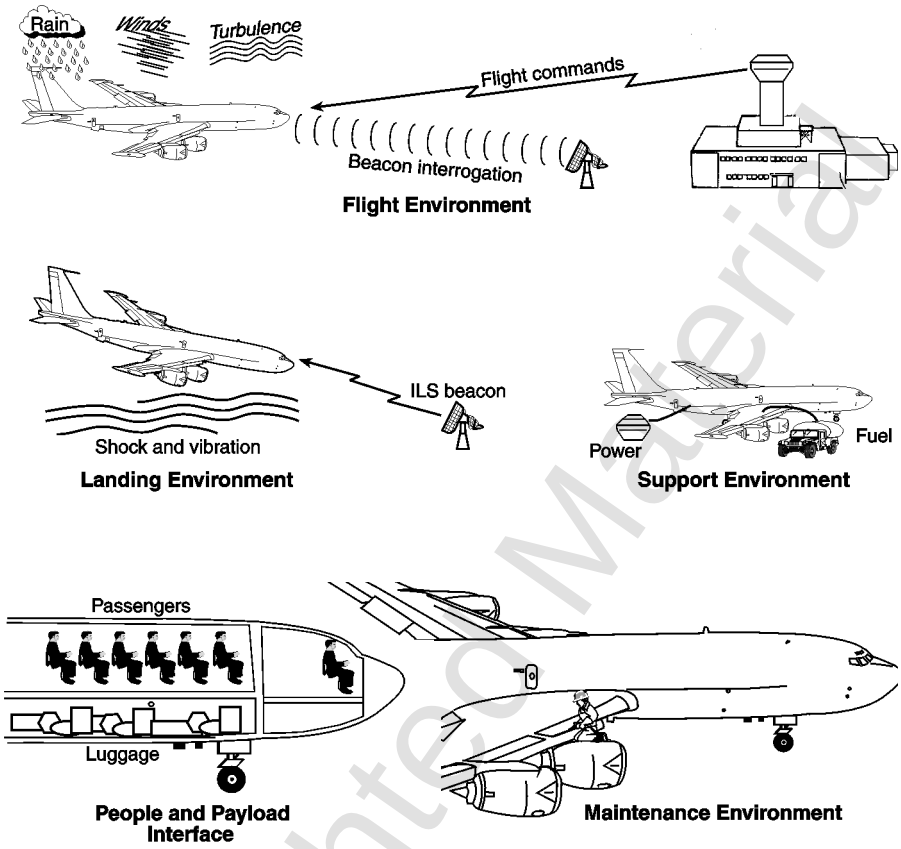

Fig. 2-3 Environments of a passenger airliner.

Support Systems Support systems are that part of the infrastructure on which the system depends for carrying out its mission. As illustrated in Figure 2-3, the airport, the air traffic control system, and their associated facilities constitute the infrastructure in which an individual aircraft operates, but which is also available to other aircraft. These are parts of the super-system represented by the air transportation system, but for an airplane they represent standard available resources with which it must interface harmoniously.

Two examples of common support systems that have been mentioned previously are the electric power grids which distribute usable electric power throughout the civilized world, and the network of automobile filling stations and their suppliers. In building a new airplane, automobile, or other system it is necessary to provide interfaces that are compatible with and capable of utilizing these support facilities.

System Housing Most stationary systems are installed in an operating site, which itself imposes compatibility constraints on the system. In some cases, the installation site provides protection for the system from the elements, such as variations in temperature, humidity, and other external factors. In other cases, such as installations on board ship, these platforms provide the system's mechanical mounting, but otherwise may expose the system to the elements, as well as subject it to shock, vibration, and other rigors.

Shipping and Handling Environment Many systems require transport from the manufacturing site to the operating site, which imposes special conditions for which the system must be designed. Typical of these are extreme temperatures, humidity, shock, and vibration, which are sometimes more stressful than those characteristic of the operating environment. It may be noted that the impact of the latter categories of environmental interactions are addressed mainly in the engineering development stage.

2.5 INTERFACES AND INTERACTIONS

Interfaces, External and Internal

The previous section described the different ways in which a system interacts with its environment, including other systems. These interactions all occur at various boundaries of the system. Such boundaries are called the system's external **interfaces**. Their definition and control are a particular responsibility of the systems engineer because they require knowledge of both the system and its environment. Proper interface control is crucial for successful system operation.

A major theme of systems engineering is accordingly the management of interfaces. This involves:

1. Identification and description of interfaces as part of system concept definition, and
2. Coordination and control of interfaces to maintain system integrity during engineering development, production, and subsequent system enhancements.

Inside the system, the boundaries between individual components constitute the system's internal interfaces. Here, again, the definition of internal interfaces is the concern of the systems engineer because they fall between the responsibility boundaries of engineers concerned with the individual components. Accordingly, their definition and implementation must often include consideration of design trade-offs that impact on the design of both components.

Interactions

Interactions between two individual elements of the system are effected through the interface connecting the two. Thus the interface between a car driver's hands and the steering wheel enables the driver to guide (interact with) the car by transmitting a force that turns the steering wheel and thereby the car's wheels. The interfaces between the tires of the car and the road both propel and steer the car by transmitting driving traction to the road, and also help cushion the car body from the roughness of the road surface.

The above examples illustrate how functional interactions (guiding or propelling the car) are effected by physical interactions (turning the steering wheel or the drive wheels) that flow across (physical) interfaces. Figure 2-4 illustrates the similar relations between physical interfaces involved in steering an air vehicle and the resulting functional interactions.

An important and sometimes less than adequately addressed external system interaction occurs during system maintenance. This activity necessarily requires access to a number of vital system functions for testing purposes. Such access calls for the provision of special test points of the system, which can be sampled externally with a minimum of manipulation. In some complex systems an extensive set of built-in tests (BIT) is incorporated, which may be exercised while the system is in its operational status. The definition of such interfaces is also the concern of the systems engineer.

Interface Elements

To systematize the identification of external and internal interfaces, it is convenient to distinguish three different types:

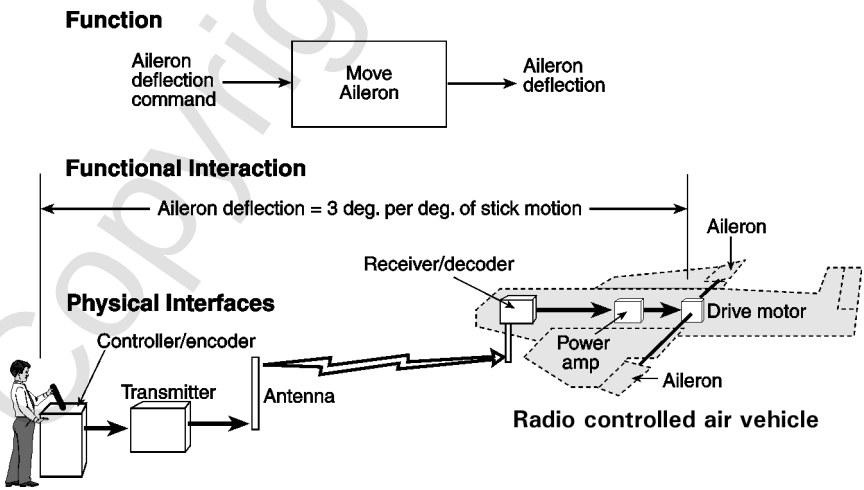

Fig. 2-4 Functional interactions and physical interfaces.

TABLE 2-3 Examples of Interface Elements

Type	Electrical	Mechanical	Hydraulic	Human-Machine
Interaction medium	Current	Force	Fluid	Information
Connectors	Cable Switch	Joint coupling	Pipe Valve	Display Control panel
Isolator	RF shield insulator	Shock mount bearing	Seal	Cover Window
Converter	Antenna A/D converter	Gear train Piston	Reducing valve Pump	Keyboard

1. Connectors, which facilitate the transmission of electricity, fluid, force, and so on between components
2. Isolators, which inhibit such interactions
3. Converters, which alter the form of the interaction medium. These interfaces are embodied in component parts or subcomponents, which can be thought of as interface elements.

Table 2-3 lists a number of common examples of interface elements of each of the three types, for each of four interaction media: electrical, mechanical, hydraulic, and human. The table brings out several points worthy of note:

1. The function of making or breaking a connection between two components (i.e., enabling or disabling an interaction between them), must be considered as an important design feature, often involved in system control.
2. The function of connecting nonadjacent system components by cables, pipes, levers, and so on, is often not part of a particular system component. Despite their inactive nature, such conducting elements must be given special attention at the system level to ensure that their interfaces are correctly configured.
3. The relative simplicity of interface elements belies their critical role in ensuring system performance and reliability. Experience has shown that a large fraction of system failures occurs at interfaces. Assuring interface compatibility and reliability is a particular responsibility of the systems engineer.

2.6 SUMMARY

Complex systems may be represented by a hierarchical structure in that they are:

Composed of parts, subcomponents, subsystems, and components

The domain of the systems engineer:

Extends down through the component level
Is as detailed as a systems engineer usually needs to go
Extends across several system categories.

The domain of the design specialist:

Extends from the part level up through the component level
Overlaps the domain of the systems engineer
Is usually limited to a single technology/discipline.

System building blocks are at the level of components and are:

The basic building blocks of all engineered systems
Characterized by both functional and physical attributes
Significant, performing a distinct and significant function
Singular, within the scope of a single engineering discipline
Common, with functions found in a variety of system types.

Functional elements are functional equivalents of components and are categorized into four classes by operating medium:

Signal elements, which sense and communicate information
Data elements, which interpret, organize, and manipulate information
Material elements, which provide structure and process material
Energy elements, which provide energy or power.

Components are physical embodiment of functional elements, which are categorized into six classes by materials of construction:

Electronic
Electro-optical
Electromechanical
Mechanical
Thermomechanical
Software.

System building block models can be useful in:

Identifying actions capable of achieving operational outcomes
Facilitating functional partitioning and definition
Identifying subsystem and component interfaces

Visualizing the physical architecture of the system
Suggesting types of component implementation technology
Helping software engineers acquire hardware domain knowledge.

The system environment, that is everything outside the system that interacts with it, includes:

System operators (part of system function but outside the delivered system)
Maintenance, housing, and support systems
Shipping, storage, and handling
Weather and other physical environments.

Interfaces are a critical systems engineering concern, which:

Effect interactions between components
Require identification, specification, coordination, and control
Require that test interfaces be provided for integration and maintenance
Include elements that connect, isolate, or convert interactions.

PROBLEMS

2.1 Referring to Figure 2-1, list a similar hierarchy consisting of a typical subsystem, component, subcomponent, and part for (a) a terminal air traffic control system, (b) a personal computer system, (c) an automobile, and (d) an electric power plant. For each system you need only name one example at each level.

2.2 Give three key activities of a systems engineer that require technical knowledge down to the component level. Under what circumstances should the systems engineer need to probe into the subcomponent level for a particular system component?

2.3 Referring to Figure 2-2, describe in terms of levels in the system hierarchy, the knowledge domain of a design specialist. In designing or adapting a component for a new system, what typical characteristics of the overall system and of other components must the design specialist understand? Illustrate by an example.

2.4 The last column of Table 2-1 lists examples of the applications of the 23 functional elements. List one other example application than the one listed for three elements in each of the four classes of elements.

2.5 Referring to Figure 2-3, for each of the environments and interfaces illustrated (a) list the principal interactions between the environment and the aircraft (b) the nature of each interaction and (c) describe how each affects the system design.

2.6 For a passenger automobile, partition the principal parts into four subsystems and their components. (Do not include auxiliary functions such as environmental, entertainment.) For the subsystems, group together components concerned with each primary function. For defining the components, use the principles of significance (performs an important function), singularity (largely falls within a simple discipline), and commonality (found in a variety of system types). Indicate where you may have doubts. Draw a block diagram relating the subsystems and components to the system and to each other.

2.7 In the cases selected in answering Problem 5, list the specific component interfaces that are involved in the above interactions.

2.8 List the test interfaces and built-in test indicators in your automobile that are available to the user (do not include those only available to a mechanic).

REFERENCES AND BIBLIOGRAPHY

International Council on Systems Engineering, *Systems Engineering Handbook*, 1998, Section 2.

E. Rechtin, *Systems Architecting: Creating and Building Complex Systems*, Prentice Hall, 1991, Chapters 2, 4, 13.