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Function and Form Relationships: A Basis for Preliminary Design

by

J. R. Rinderle

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James R. Rinderle
Mechanical Engineering Department
Carnegie Mellon University
Pittsburgh, PA. 15213

Abstract

During preliminary design, designers must evaluate the relative merits of many alternative concepts. Experienced designers are able to reason about basic relationships between the physical structure of alternatives and performance of a device and can therefore eliminate many alternatives without the need for design detailing. Such form-function relations exist for individual components and devices due to basic engineering principles. They can be codified and used as a basis for a structured system able to assist less experienced designers. Because these relationships do not depend on design details, such a system facilitates top-down design and the early evaluation of design alternatives. Basic relations between form and function for individual components can also be aggregated to represent subassemblies, assemblies, devices and so forth. This facilitates modularity in design. The relations can be refined as the design becomes more detailed, providing resolution in evaluation commensurate with the level of design detail.

Introduction: A Design Scenario

How might an individual design a device, e.g. a printhead positioning mechanism for a small dot matrix printer? The designer will consider a variety of design configurations, some of which might already exist in similar products and some of which are likely to be novel design concepts. Three design concepts, each from a commercially successful product, are shown in Figure 1. The figures illustrate some of the alternatives available to the designer including motor position, speed reduction method, bearings, guide ways, and drive media. How does the designer choose which, if any, of these design concepts is best for his particular application? The most obvious and least practical method is to finish the design for each concept and simply select the best. Although only three concepts are shown, it is clear that many more are possible, and in fact very creative designers could become a liability in that they might create an enormous number of design alternatives, each of which would have to be designed in detail before the final design could be selected. This is certainly not what designers do, so how then are alternative design concepts evaluated? It seems that designers consider the relative merits of the alternatives in terms of physical configuration, e.g., which will be smaller, performance, e.g., which will be most precise, and manufacturability, e.g., which will have fewer and lower cost parts? The evaluations are goal directed (How can it be made smaller?) and judicial (Will it be light enough?) and are made prior to design detailing.

It may be that none of the existing configurations meet all of the objectives of the designer. He might then suggest alternative configurations which include, for example, a motor assembly from one printer, standard guide ways from a second, a novel belt or cable configuration, and perhaps some imprecisely specified items such as a "compliant coupling." The designer will evaluate this configuration in much the same way that he evaluated existing devices, once again addressing physical arrangement, performance and manufacturing. Fundamental questions driving this evaluation include whether the configuration will meet specifications and how the device can be altered to make it perform better, cost less, fit into a smaller place and so on.

With one or more basic configurations in mind, a designer will focus his attention on some critical group of components e.g., cable configuration. He might consider how the cable length and pulley support structure influence positioning accuracy and weight, and might consider how that portion of the device could be improved by rearranging

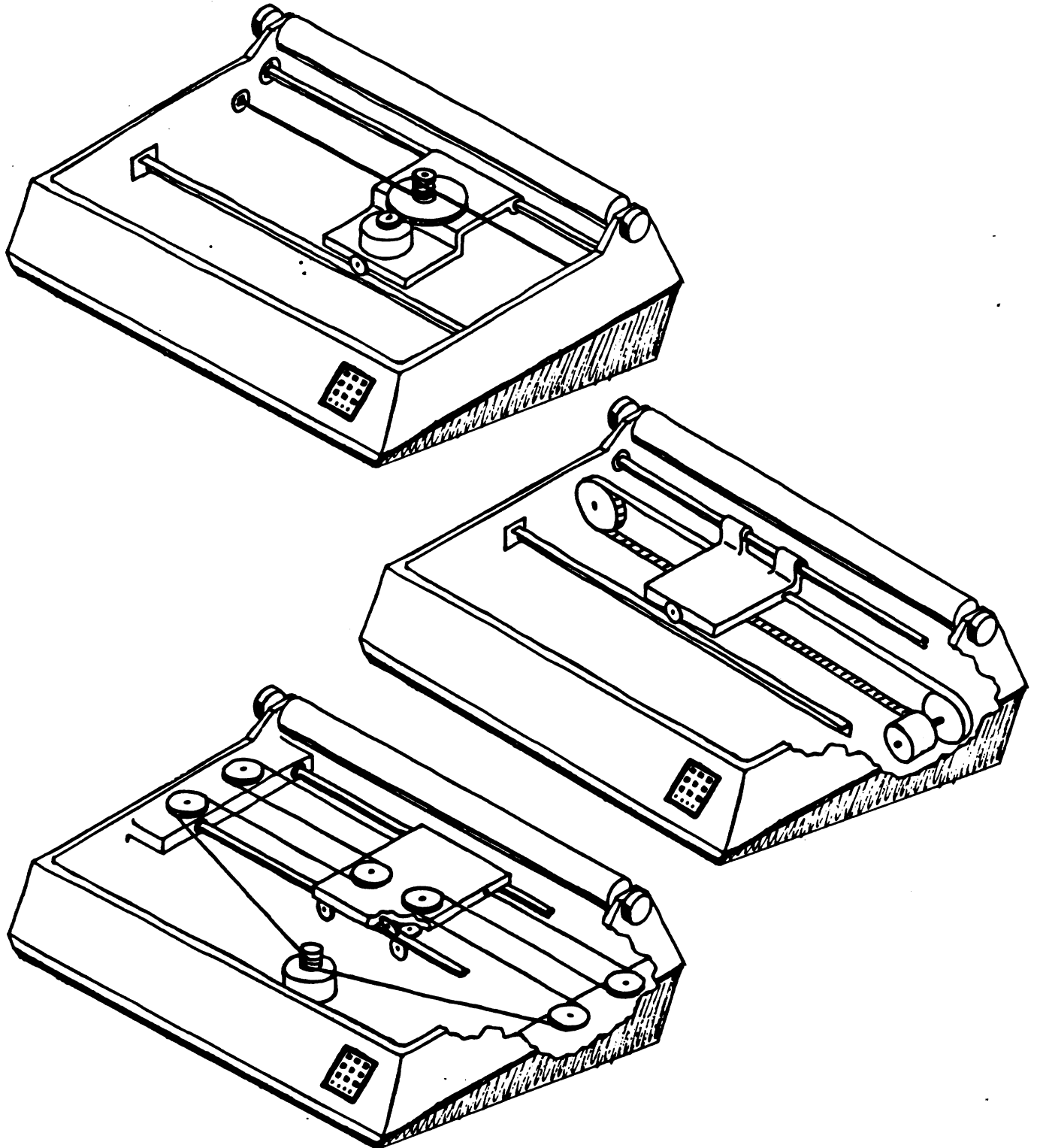


Figure 1: Three commercially successful printhead positioning design concepts.

components or selecting different components altogether. In this way the design will gradually become more complete, the designer will consider more of the design details, and the impact of design decisions will be evaluated at successively greater levels of detail. Design detailing progresses (with occasional backtracking and reconsideration) until the device is completely specified and the designer is satisfied with the configuration and anticipated performance of the device. Subsequently, the design will be subjected to testing, more detailing, refinement, component optimization, and so forth.

It is clear from this contrived scenario that preliminary design encompasses many methods and activities. Designers work with standard components, existing assemblies, such as the motor/gearbox, novel or custom components, and some vague functional items such as a rigid support or a compliant coupling. Designers consider the merits of alternative design concepts and preliminary design configurations, reasoning how certain design features influence relative performance and manufacturability. It seems that this is an essential feature of the design process not captured in various definitions, descriptions or prescriptions for design [1,2]. Whether evaluating alternatives, configuring subassemblies, selecting components, or detailing fasteners, the designer is explicitly or implicitly considering the relationships between the form which a device will take, the functions it must perform and the means by which it will be fabricated. Relations among function, form and fabrication determine the difficulty of the design task and the efficacy of the designed artifact [3]. Furthermore, the differences in function, form and fabrication relations from one design domain to another have an enormous impact on the methods employed by designers. Indeed, it may be that the ability to know of and reason about subtle relationships among function, form, and fabrication are the characteristics which differentiate the experienced designer from the novice.

Structures In Function-Form Relationships

There are many designs which satisfy any one set of functional requirements, therefore there cannot be a unique relationship between the function and the form of a product. How then is the structure of a form-function relationship reflected in the overall design quality and the difficulty of the design task.

The notion of a function-form relation is most easily understood in a transformational sense. We could say that the product requirements, encoded as a set of

functional specifications, are transformed by the designer to the physical domain as a description of form [4]. In this way we can think in terms of relationships between design parameters, which describe the form of the object, and functional requirements which describe performance. It is of course difficult to reason how each design parameter, such as bearing separation distance will influence basic functional requirements, such as positioning speed and accuracy. It is useful therefore to exploit structure in both performance requirements and the physical configuration of the device itself in describing form - function relations. The form of the object as a whole can then be represented as the collection of components and a description of the interaction among components. The functional requirements for the device can also be decomposed into some set of lower level functions. We therefore have a possibility of having distinctly different decompositions in function and in form.

An idealization of the printhead positioner illustrates how form and function can be decomposed. The basic functions of the printer can be thought of as *positioning the paper*, *positioning the printhead*, and *printing*¹ as shown in Figure 2. The printhead positioning function can be achieved by both *guiding* and *driving* with the *guiding* function achieved by restricting motion in five of the six rotational and translation[^] degrees of freedom. This functional decomposition could apply to any one of the three configurations shown in Figure 1. Physical decomposition can also be shown, as in Figure 3. In this case individual components are shown with their relationships to other components. The structure of and the relationships between the functional and physical decompositions, shown in Figures 2 and 3 are of particular interest.

The functional decomposition is a tree type of graph in the figure. Although this need not be the case it is common because the tree structure is a natural representation of the divide and conquer problem solving paradigm. The physical decomposition is shown as a much more general type of graph structure, representative of the multiple interactions of each component.

Since the functional and the physical decompositions are each descriptions of the same device, they must be related. If we change a single component, e.g., the motor, we directly influence the *drive* function. However, since motor weight and torque also change we might also change bearing loads and therefore certain *guide* functions. If

¹This functional decomposition is not unique and is itself a design decision.

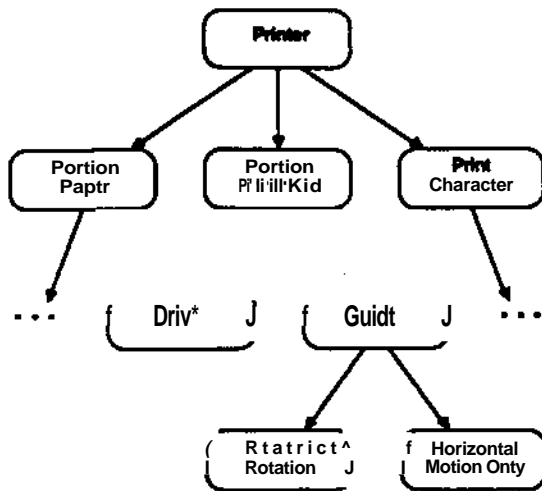


Figure 2: Functional decomposition of a printhead positioning system

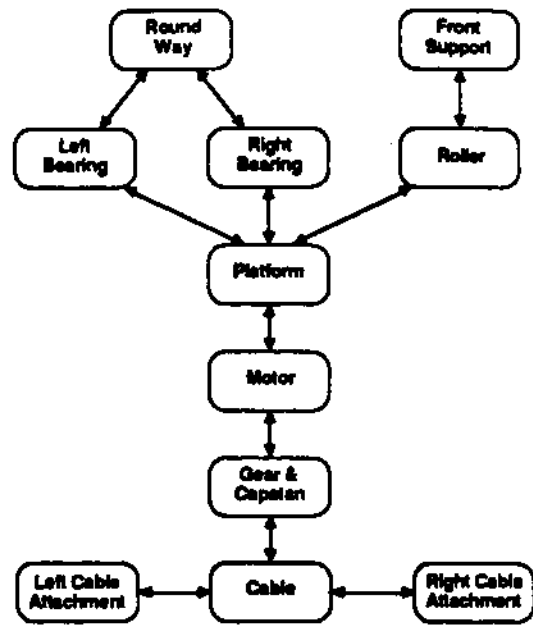


Figure 3: Physical decomposition of a printhead positioning system

these relationships are thought of as links between domains then in this case we have a one-to-many type of relation between the physical domain and the functional domain. The converse is also true. Changing a single function such as *drive* speed may require changing the motor and the bearings so a one-to-many relationship exists between the functional and physical domain as well. The physical and functional domains are linked in this way. The number and complexity of these links is determined by the design itself. The difficulty of the design task and the design quality are related to the structure of these form-function links.

The conceptual design of an integrated circuit to compute the RMS value of a digital signal is an interesting contrast in function - form relations. The circuit must square the input, compute the running average, and compute the square root of that average. The squaring function can be decomposed into a sequence of add and shift operations as shown in Figure 4 The shift function can be implemented with a ladder arrangement of store functions, the store function implemented with a particular arrangement of logic functions and so forth down to the lowest functional level. Figure 5 is a stylized circuit diagram of a portion of the device which shows the nature of the physical decomposition

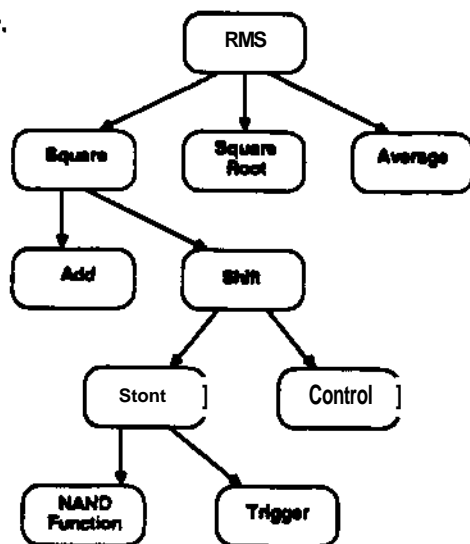
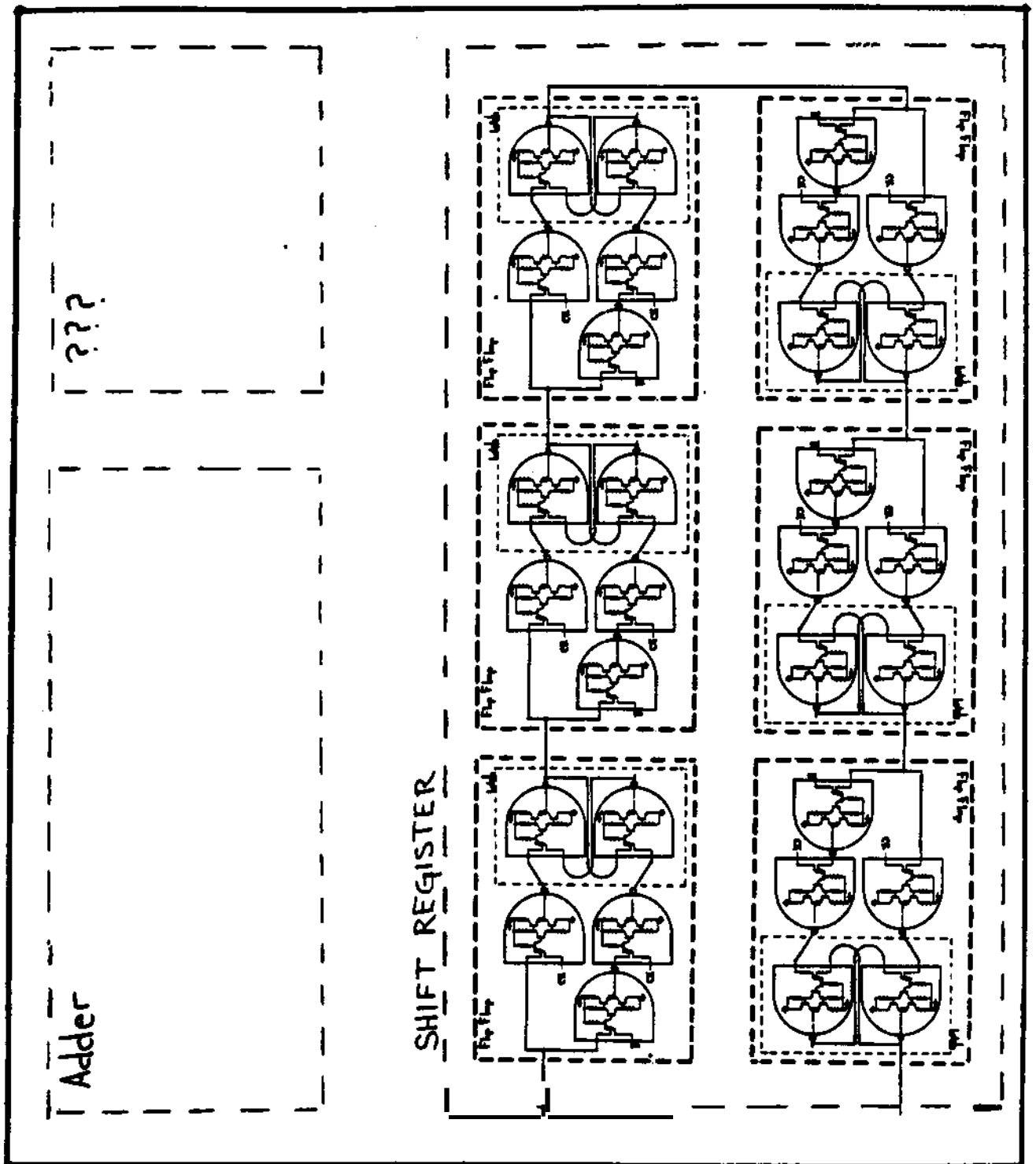


Figure 4: Functional decomposition of an integrated circuit



FigureS: Stylized circuit diagram and physical decomposition of an integrated circuit

of the LC. The nature of the function-form relation for the circuit can be easily understood from the thought experiment of observing what is happening at a particular location on the silicon wafer where the real circuit is etched. We might very well think of a particular transistor which is used to implement some logic function such as NAND. That NAND gate might well be part of a flip flop used to store data. The storage function could be part of a register, a register part of the integer square function, and so forth up to the highest level physical description of the integrated circuit. In this very special case we have a one-to-one correspondence between a physical decomposition of the circuit and a functional decomposition of the circuit. Not only does this isomorphism result in a one-to-one correspondence between function and form at the lowest level but it also implies that the physical decomposition must be tree-like in nature to match the tree type structure in function. As a result, there is matching at all levels between the form and function decompositions and therefore a higher level function, such as shift, can be identified uniquely with a specific region on the integrated circuit. A high level correspondence does not exist for the printhead positioning problem. In this case, a high level function, such as *guide* does correspond to some collection of components as shown in Figure 3, however, many of those same components influence other functions, such as *drive*. Why do such isomorphisms between function and form exist for this type of circuit but not for the printhead positioner? It seems fair to say that they exist both because the design is automated and so that it can be automated. This approach and others are discussed in the following sections.

Strategies for Design

Different types of form-function relations obviously have important ramifications on the design process. It might also appear that these relations are reflected in overall design quality in much the same way. This merits further discussion.

The design of devices in which physical structure is isomorphic to the functional structure can be carried out in a completely modular and hierarchical manner. Although modularity and hierarchy are generally favorable attributes in a design, they are not usually obtained without cost. The hierarchical decomposition of function is often obtained by imposing additional constraints upon the relationship between functional subsystems. If the effects of these additional constraints is minimal then satisfying the subfunctions separately will result in a design nearly as good as could have been obtained without decomposition. In the VLSI domain, decomposition was achieved by imposing

certain restrictions on spacing, timing, impedance, and power. A few square microns of silicon might have been required to accommodate these additional constraints. If the same strategy had been adopted in the 1940's prior to the advent of transistors and integrated circuits, we might well have found that the decomposition strategy was very costly indeed.

Mechanical designs can sometimes be decomposed such that the physical arrangement is isomorphic to the functions. It is often the case, however, that such a decomposition results in heavy, costly, and poorly performing devices. Why is this so? An essential feature of such structure is the non-interacting nature of sub-system design decisions. The over-design required for example to make positioning performance independent of bearing size and losses is obviously significant. Furthermore, the ideal form-function structure may preclude important economies often gained by integrating components. So although the design method might be simpler, the design itself may not be better.

Forsaking the ideal form-function structure implies that design decision making will be more complex. Nevertheless, many experienced designers are able to reason about very complex devices and quickly identify configurations which will operate well. It seems that experienced designers are also able to find some middle ground in complexity by identifying individual features, variables, or relationships which dominate the performance and the cost of the design. Designers do this without resorting to elaborate or complex mathematical approaches and without perusing encyclopedic data. These abilities, however, seem only to be acquired with extensive experience. Nevertheless, it seems that some structure exists in design decision making which enables designers to reason about fundamental relationships between the form and function of a product.

The Basis for Function-Form Relationships

The fact that a designer can look at a motor and determine whether it is a ten horsepower, a one horsepower, or a one-tenth horsepower motor, and that he can look at a gear reducer and say with confidence that it is a worm gear mechanism, seems to be prima facie evidence that certain form-function relations exist. If this sort of knowledge could be gained only on an experiential basis, or if the relations for each small class of components had to be compiled individually, it would be difficult, at best, to take much advantage of these form-function relationships. It is fortunate then that these

relationships exist as a result of fundamental limitations imposed by physics and the state of the art in engineering.

The physical and engineering limitations on energy density are common and useful for the purpose of relating form to function. The coil spring once again serves as a simple example. Neglecting spring-end configurational details, it is easy to show that the weight of a simple coil spring is proportional to the spring stiffness and the square of the maximum allowable deflection. It is the case then that we have a relationship between an attribute of form, in this case weight, and a functional specification of stiffness and deflection. It is not surprising that such a relationship should exist since the energy stored in a helical spring is proportional to the product of stiffness and the square of deflection. This relationship between form and function, or in this case, weight, stiffness and deflection is really a statement that there is a maximum average energy density associated with conventional coil springs. Since a coil spring is loaded principally in torsion, it is not surprising to find that the maximum average energy density for the torsion bar is the same as the coil spring and therefore the torsion bar (with a moment arm) will exhibit the same type of relationship between spring weight, stiffness and maximum deflection as the coil spring. Leaf springs also exhibit fundamentally the same relationship modified to a small degree by the fact that a leaf spring is loaded in bending rather than torsion.

Simple relationships of this type make it possible to draw inferences about the function of a device from its physical arrangement alone, however, a much more important benefit of such relationships is that a designer can evaluate certain alternative design configurations without completing a detailed design. With the simple spring case, the designer can determine, a priori, that a coil spring or torsion bar will be lighter than a leaf spring and that while certain tradeoffs exists between torsion bar diameter, length, and moment arm length, the spring weight will be basically unchanged.

Similar relationships exist for many mechanical components precisely because designers have sought to make the most economical use of the materials which are available to them. Function-form relationships governed in large part by energy considerations can be found in gears, motors, bearings and most other devices which transmit or transduce power or which supply, or support forces. Of course the relationships which exist vary from one type of component to another. For example, in the case of motors and gears we find that the weight of the component is more nearly in

proportion to the torque than it is to power transmitted. Nevertheless, certain relationships exist which can be readily identified for broad classes of mechanical components.

It is because of the similarity of function-form relations that it is often possible to escape even one more level of design detailing in selecting the best of many design configurations. In the case of the spring, the designer is able to reason about the basic weight and size of a spring even before deciding whether that spring will take the form of a coil spring or leaf spring. Even higher levels of abstraction are possible as springs are combined with other components to make suspension elements, vibration absorbing devices, mechanical filters, and so on. In these cases it is possible to reason about the relationships between the performance of some device such as a vibration absorber, and the basic physical parameters which describe that device, for example the size and weight of the device. The existence of this hierarchy in function-form relationships facilitates the reasoning about design configurations prior to the completion of the design details.

Reasoning in this way is the norm in preliminary design carried out by skilled designers. This is in stark contrast to some methods proposed for computer based automatic mechanical design. In many of these systems an enormous design space is searched (however intelligently), to determine which of many design alternatives is the best. This contrasts with the directed, top-down approach to design exhibited by skilled designers.

Function-form relations have been the focus of the discussion to this point. Some fundamental form-fabrication relations also appear to exist based on similarly simple and fundamental yet different relationships. Although these relationships will not be discussed herein, it is worth noting that common and simple costing procedures work well for very sound reasons.

Aggregating Form and Function

At issue is the form and function of the device as a whole, not simply the individual components. It is critical therefore to address how the characteristics of individual components can be aggregated to represent the device characteristics. If the form-function relationships described previously for individual components are to be useful, they must be combined to make higher level descriptions of both the form and the function of a device. If the only attribute of form is weight, then it is simple to see how

we can determine the weight of the overall device simply by summing the weight of the components. As important as weight is, however, it is not the sole determiner of whether or not a form is acceptable. Many other factors are also important, notably the total volume of individual components, the packed volume of components in a device, and most importantly the way individual devices mate with adjacent components.

Certain of these relationships obviously require a substantial amount of information on the detailed geometry of components. This implies that at least to some extent the design has to be detailed, which is contrary to the objective of evaluating design configurations prior to the detailed design phase. This barrier may not be so severe because once again sound engineering principles driving the design of components often result in certain families of standard configurations. Even when a wide variety of shapes exist for a class of components it is often the case that the shapes can be categorized in terms of the functional specifications. The coil spring is once again a good example. Springs with similar stiffness and deflection characteristics can be obtained in a wide variety of lengths and diameters. One or the other may be preferable in some absolute sense but generally the designer is free to choose which spring is used. It is clear that there is a continuum of alternatives that depends only on the preferences of the designer, presumably influenced by other constraints. Many components will have similar flexibility in design configuration. To design the overall device it is therefore necessary to simultaneously consider the shapes, sizes and mating of many individual components. This is an enormously difficult task requiring a high level of geometric reasoning, but it is a task at which human beings are often adept, particularly when data is presented to them in an appropriate and convenient form.

It seems practical therefore, in the short term, to rely on the individual's spatial reasoning ability. After the designer, for example, has explicitly or implicitly specified the deflection and stiffness of the spring, he could be shown an appropriately sized cylinder indicating the size of the component which would be required and perhaps some auxiliary cylinders indicating alternatives. The designer would then choose among the alternatives and could position the spring in three dimensional space. Although it is possible to explicitly represent spatial relationships among individual components, subassemblies and so forth, the efforts may outweigh the benefits. Simple location and orientation supplemented with pictorial presentation may be sufficient and is certainly simpler and more expedient than representing the entire geometry and topology of the

design as a true solid model.

The aggregation of form is difficult but does possess one convenient and general characteristic not exhibited in the aggregation of function. In the consideration of form there is a dominance based on physical proximity. When the shape of some component changes it has a localized effect on the geometry of the product and on adjacent components, but the magnitude of the trickle down effect is relatively small. This is not the case when we consider functional changes. Changing any stiffness or mass within a suspension for example, may have a significant effect on the natural frequency of the suspension. It is common for a function of a device to be influenced by a large number of components or parameters which are separated to a great extent in space. It is therefore necessary to consider how the overall performance of the device can be based on simple descriptions of the functions of each of the constituent components.

It is perhaps easiest to think about the way in which an individual component can influence the overall function of a product by considering how that component can interact with others. At the lowest level we can characterize the interaction between two components in terms of some force and velocity specifications. Replacing a component with a set of forces and motions identical to those which existed between the original components will leave the functioning of the rest of the device unchanged. Therefore, it is only necessary to properly describe the nature of force and motion which occurs between components. Formally one could say that completely characterizing the force-velocity behavior of a device is both necessary and sufficient for describing its influence on the overall performance of the device. Force and velocity themselves might be the variables of most direct interest in certain kinematic devices. However, in different types of devices, for example engines, we might be more concerned with power and torque-speed relationships. A specification of this form is equivalent to specifying a relationship between a generalized force, engine torque in this case, and a generalized velocity, engine speed in this case since the product of torque and speed is power and their ratio is a mechanical impedance. The design of mechanical devices is often dominated by power considerations, therefore a representation in terms of power and impedance may be the most convenient way of describing interaction between components. Rigid constraints, sliding contacts, hinged joints and most other common interactions are easily described in terms of six axis impedance and power relations.

Representing all components and interactions among components by complete

power and impedance relationships preserves all the functional information of a dynamic system. It does not, in and of itself, solve the difficult problem of predicting and characterizing dynamic system performance. Direct application of this method results in a large set of dynamic and kinematic equations which must be solved simultaneously, often as a function of time. Depending on the complexity of these equations, certain algorithmic solution methods exist which make it possible to quickly determine the performance of the overall device. This however, is not the main benefit of aggregating function. More importantly the designer can use very simplistic functional descriptions of components during the preliminary design phase to assess the viability of a particular design configuration. Furthermore, simplified models of function make it easier for the designer to develop insight into the performance of the overall device. As design detail increases the designer is able to use more realistic models of function to obtain more precise predictions of overall performance. The designer may, for instance, represent the hardening characteristics of a conical spring when proceeding to more detailed phases of design. Although different solution methods will be required, the structure of the form-function relationships do not change and therefore the designer is better able to reason about ways in which the design can be improved.

Conclusions

Skilled designers reason about the relationships among the form which a device takes, the function which it performs and the means by which it will be fabricated. This is true during even the most preliminary stages of design and for products in which individual design decisions influence many functions of the product. Many of the relationships between form and function, which experienced designers use routinely, result from fundamental physical limitations such as allowable energy density. Relationships of this sort can be used as a basis for relating form to function for broad classes of engineering components. Component level relationships can be aggregated by describing interaction in terms of impedance and power. As a result it is possible to reason about basic configuration-performance trade-offs prior to design detailing, thereby facilitating top-down design and early evaluation of design alternatives. The ability to define more precise models and to combine components permits a modular and hierarchical approach to design, encourages standardization and reuse of subsystems, provides for variable resolution in function evaluation and allows the designer freedom in defining customized components and functions. A structured design system of this type

will not replace the designer but it is expected to be useful to less experienced designers in evaluating and selecting among a wide variety of alternative design configurations.

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