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by

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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 and the performance of a device and can therefore eliminate many alternatives without the need for design detailing. Because these relationships between form and function do not depend on design details, they facilitate top-down design and the early evaluation of design alternatives.

In mechanical designs these relations are often tightly coupled and the devices they represent are often composed of highly-integrated components where the interactions among the components are essential to the function and economic execution of the design. This assertion runs counter to design methodologies in other engineering fields, such as software design and circuit design, that advocate designs in which each component fulfills a single function with minimal interaction. Because of the geometry, weight, and cost of mechanical components, converting a single functional requirement into a single component is usually not practical. Each component may contribute to the performance of more than one function, and the performance of each function may be distributed over many components. In fact, most mechanical components perform not only the desired function, but also have many additional, unintended behaviors. In good mechanical designs, these additional behaviors often are exploited.

We discuss a mechanical design strategy for transforming the system specifications into a description of a realizable physical system. It is our hypothesis that, by utilizing a description of the desired functionality of a mechanical system and a corresponding description of classes of physical components, we will be able to generate a design of a physical system that takes advantage of the multiple functions of its components. The methodology is described and its application to the design of mechanical power transmissions is discussed.

Structure in Function-Form Relationships

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. 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. 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.

To understand relationships between design parameters and functional requirements it is useful to exploit structure in both requirements and the physical configuration of the device itself. 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, shown in Figure 1, 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 translational 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

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

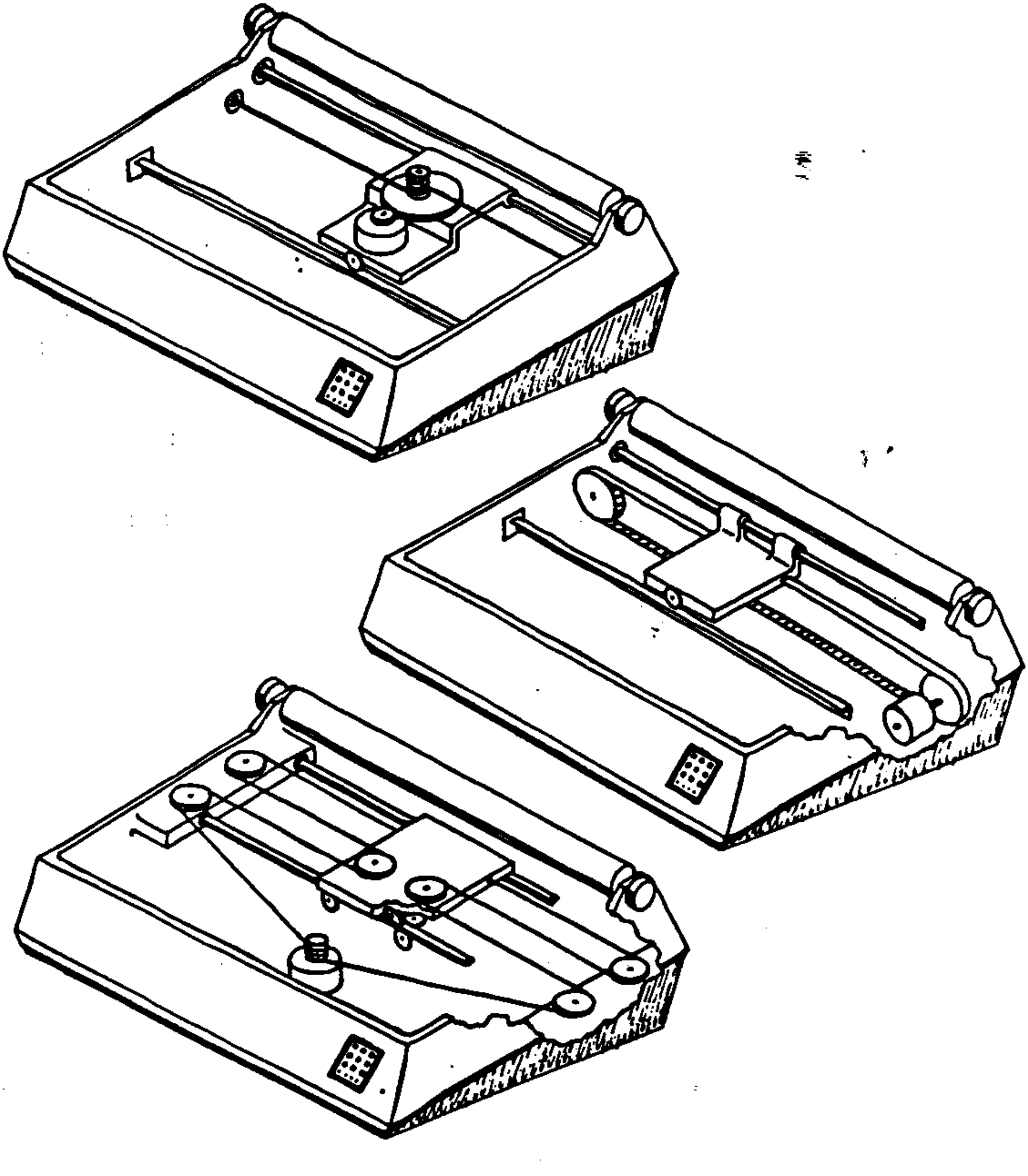

Figure 1: Three commercially successful printhead positioning design concepts.

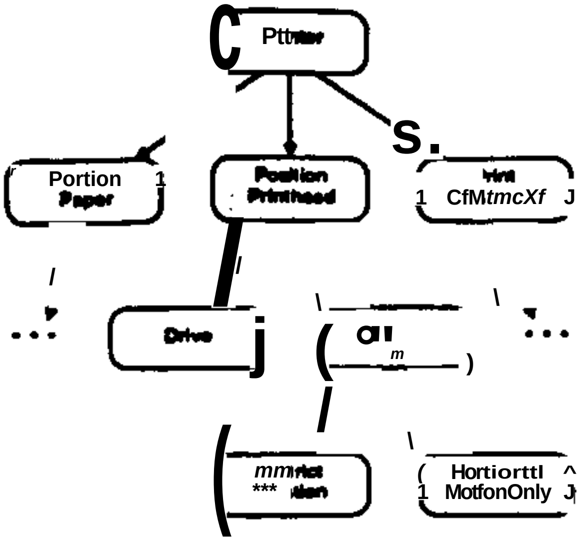

Figure 2: Functional decompositon of a printhead positioning system

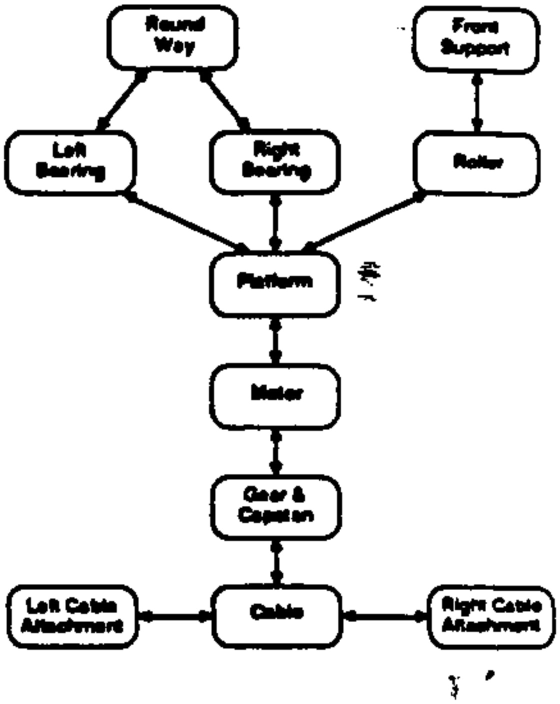

Figure 3: Physical decomposition of a printhead positioning system

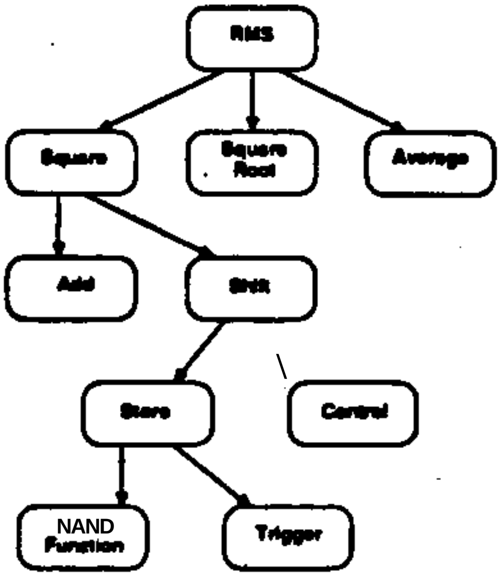

Figure 4: Functional decompostion of an integrated circuit

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 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 ^ 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. These low level functions are then transformed into pre-existing circuit fragments and recombined to achieve overall circuit functionality. The resulting nature of the function-form relation for the circuit can then 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 pan of a flip flop used to store data. The storage function could be part of a register, a register pan 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

The structure of form-function relations has 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 often useful for relating form to function. A simple coil spring 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 also 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.

An important benefit of such a relationship 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 pan 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.

A Structured Synthesis Strategy for Mechanical Devices

During the design process the designer transforms an abstract functional description of a device into a physical description which satisfies the requirements. In this sense, design is a transformation from the functional domain to the physical domain. However, the basis for selecting favorable transformations and methods for accomplishing transformations are not well understood. Our work is an effort to discover the desirable characteristics of these transformations and develop a structured approach for transforming a device specification into a physical description, thereby creating design alternatives. We contend that form-function relations provide a strong basis for selecting favorable design transformations and that by combining these with the simple guideline of integrating functionality, a robust and useful structured approach to design can be defined. This approach can be used to design a device configured from classes of known components.

A Strategy for Mechanical Design

The direct functional decomposition of a set of device specifications and subsequent one-to-one matching of individual functional requirements to physical components results in weak designs for two reasons. The first of these is that by matching individual functions to some collection of components we forsake the opportunity to integrate functions into more compact or economical collections of components. Secondly, components provide not only the desired function but also many additional, unintended behaviors. The following simple examples illustrate the problems with direct decomposition and demonstrate one method that helps resolve them.

> Consider the design of a speed reducing device. Specifications for the device are given as:
>
> - The ratio of input to output speed must be 8:1.
> - Hie input and output shafts must lie at right angles to each other.
>
> This set of specifications is already functionally decomposed into two independent functional requirements, the 8:1 reduction and the right angle requirement. The most direct solution is to match each of the individual requirements with a separate piece of physical hardware. A spur gear set may be selected because its behavior matches the functional requirement of an 8:1 reduction. Then a bevel gear set may be selected because its behavior matches the functional requirement of a right angle between the input and output shafts. The resulting physical description then consists of a spur gear pair connected to a bevel gear pair. So, by matching between the decomposed functional description and the behavioral descriptions of known components a physical configuration can be generated. However, this simple case demonstrates that one-to-one matching usually results in a poor design because the resulting device is more complex than is necessary. If instead the matching is done so that functional integration is emphasized, then more compact and economical designs result. Here, by using the form-function relations for bevel gears, it can be determined that a bevel gear provides both of the functions required, a reduction *and* a right angle between the input

and output shafts. So, matching *both* functions to a bevel gear results in higher degree of function integration and a more economic execution of the design.

This example illustrates that combining functions in a single device will often result in a superior design. The difficulty lies in properly matching the functions in the specification to actual components. Form-function relations of the components provide a means to this end because they express the relation between behaviors and physical form. However, matching the functional specifications to the physical form of the components is not always as straightforward as in the previous example. The following example demonstrates some of these complexities and some methods for accomplishing an economic execution of the design.

Consider the design of another speed reducing device. Specifications for the device are given as:

- The ratio of input to output speed must be *40:1*.
- The input and output shafts must be at right angles.

If the catalogue of available items consists only of straight bevel and spur gear sets, we find that there is no single component which is capable of providing the 40:1 speed reduction. So an immediate matching between these specifications and a physical description is not possible. Instead the specifications must be *transformed* into a form that allows for matching between the specifications and device behavioral characteristics. In this case we apply a transformation which decomposes the specified functionality into a collection of equivalent functions; for example, a 5:1 speed reduction followed by an 8:1 speed reduction and a right angle between the input and output shafts. Note that this transformation preserves the overall functionality expressed in the original specifications. This is an important characteristic of all transformations; that they be function preserving, otherwise the completed device will not meet the specifications. The decision to decompose the specifications in this manner is guided by the form-function relations for the components. They represent the fact that no single spur or bevel gear pair can have a reduction ratio greater than 8:1. Therefore, this particular form-function relation is used to guide the decomposition of the 40:1 reduction ratio into two elements neither of which exceeds an 8:1 reduction ratio. After this decomposition, it is possible to match each of the individual functions, the 8:1 reduction, 5:1 reduction and right angle, into a physical component; however, direct matching would result in a design which is large, costly and complex as was shown before. Alternatively, we can seek *groups* of functional elements which closely correspond to available physical components. In this case, by considering the form-function relations for the known components, bevel and spur gears, we find that we can group or associate the 5:1 speed reduction with the right angle function. So we can view the specifications as consisting of two groups; a 5:1 reduction coupled with a right angle, and an 8:1 reduction. We now find that we can match each of these *groups* with a physical component; specifically, a bevel gear set can satisfy both the right angle requirement and one of the reductions, and a spur gear set can satisfy the second reduction requirement.[2] In this case we have not only achieved multiple functions with a single component but we have identified a particularly favorable selection of components by grouping individual functions into collections that closely corresponded to real physical devices.

This example illustrates the integration of multiple functions into single components and

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[2] The relative configuration of the two components can be selected to maintain coplanarity of the shafts or to achieve an offset. The way in which components are configured relative to each other is critical to both function and geometry.

the value of function preserving transformations intelligently applied to the device specifications. It also demonstrates the role of form-function relations in guiding these processes. However, the approach used above will not always be clear or unambiguous. The matching between specified functionality and component behavioral characteristics is not always as perfect Physical components have many behaviors and an exact match between specifications and component behavior will not always be possible, If this is the case, unintended behaviors will be introduced into the device. Consider if the lexicon of known components used in the example above included worm gears. A worm gear introduces an offset and a right angle between the input and output shafts. It also can provide a 40:1 reduction ratio. Therefore, a worm gear could be used to integrate all of the desired functionality, 40:1 reduction and right angle, into one component resulting in a lighter, simpler device. But, it also introduces a behavior not required in the specifications, an offset between the input and output shafts. This configuration is desirable only if this behavior is acceptable. So, the specifications must be transformed and matched to the components incrementally and the the desired functionality of the device must be maintained after each transformation, grouping or matching of the specifications.

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.

Form-function relations may be used in the conceptual design of mechanical systems comprised of standard components. The proposed methodology for the synthesis of mechanical designs recognizes and exploits the unintended physical and behavioral attributes of mechanical components. Our goal is to synthesize integrated designs in which a function may be distributed over several components and in which a single component may perform several functions. The methodology is driven by two fundamental strategies: function integration and utilization of unintended behavior. These strategies are implemented through the use of a transformational approach to design which relies upon an independent representation of the desired form and function of the device and an interdependent representation of the form and behavior of the standard components.

The major strengths of this approach are:

- Its use allows for the design of new configurations without requiring a fixed decomposition set before the design process begins.
- It describes a generative approach to design that investigates only 'reasonable' alternatives. Instead of a blind search for desirable configurations, the form-behavior graphs for the known components provide the knowledge necessary to 'intelligently' find alternatives.
- It allows and encourages the investigation of design alternatives in parallel. In addition, a useful mechanism for selecting which design alternative to consider, at any one time, is described.

In summary, we have begun to establish a methodology for the representation and transformation of device specifications into physical components. We believe that developing a methodology for mechanical design that formally and explicitly accounts for the multiple behaviors and form-behavior relations inherent in physical components provides a more rigorous, yet useful approach to the design of devices using standard components. Not only will the methodology enable the creation of more intelligent software systems for design, but it will also enrich design education and aid practicing designers by providing a more rational, understandable framework for the transformation from the functional to physical domains.