Function Sharing in Mechanical Design*

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Abstract

Function sharing in mechanical design is the simultaneous implementation of several functions with a single structural element. If automobiles were designed without function sharing they would be relatively large, expensive and unreliable. But because elements like the sheet-metal body implement many functions (electrical ground, structural support, aerodynamic faring, weather protection, and aesthetics among others) automobiles perform better and cost less than a non-function-sharing alternative. This paper describes how function sharing can be viewed as a computational design procedure that produces efficient designs from modular designs. The function sharing procedure consists of three steps: 1) a structural element is deleted from the design; 2) physical features that can provide alternative implementations of the function(s) of the deleted element are found; 3) modifications are made to the design to accentuate the desired properties of the features found in step 2. We have chosen mechanical devices that can be described functionally as a network of lumped-parameter idealized elements as a domain for exploring function sharing. Such devices include pressure gauges, accelerometers, and hydraulic cylinders.

1 Introduction

Function sharing in mechanical design is the simultaneous implementation of several functions by a single structural element. For example consider the difference between the devices shown in figure 1. The devices are functionally similar, yet the upper device is much more efficient because each structural element of the device implements several functions. This paper describes how function sharing can be viewed as a computational design procedure that produces efficient designs from modular designs. The objective of this work is to develop ideas that will lead to enhanced design teaching, better computational tools for design, and increased understanding of general issues in machine intelligence. We present our ideas with five sections: the concept of function sharing, domain description, the function sharing procedure, an example, and discussion.

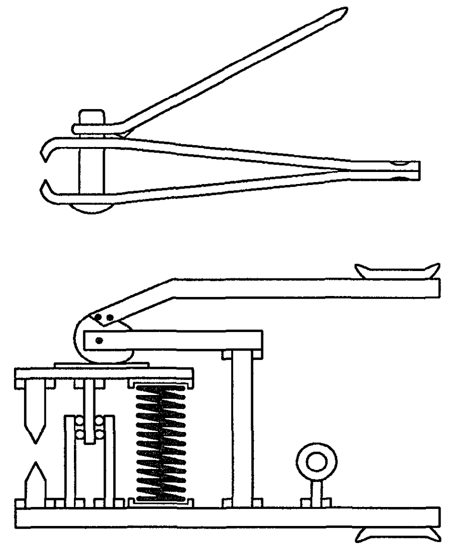

Figure 1: Example of function sharing

2 The Concept of Function Sharing

Designers must somehow represent a design in terms of its constituent functional elements. We call this representation a *schematic description*. Designers must also represent the structure or physical properties of the design. We call this representation a *physical description*. Physical descriptions correspond in some way to schematic descriptions of the same design. Whatever language is employed for the representation of schematic and physical descriptions, we define function sharing as a correspondence between several elements in a device schematic description and a single element in a device physical description. In the case of the devices shown in figure 1, some of the functional elements in a possible schematic description language might be *cutter*, *actuator*, or *finger interface*. The structural elements in a possible physical description language might be the geometrical descriptions of each separate part. Whenever a single structural element maps to

*This paper describes work performed at the Artificial Intelligence Laboratory of the Massachusetts Institute of Technology. Support for the laboratory's research is provided in part by the Defense Advanced Research Projects Agency of the United States Department of Defense under the Office of Naval Research contract N00014-85-K-0124, and the National Science Foundation under grant DMC 8618776.

more than one functional element, then the device exhibits function sharing.

2.1 Function sharing is important

If automobiles were designed without function sharing they would be relatively large, expensive and unreliable. But because elements like the sheet-metal body perform many functions (electrical ground, structural support, aerodynamic faring, weather protection, and aesthetics among others) automobiles can be manufactured relatively inexpensively and can perform relatively well. As a general rule, function sharing is a good design strategy for high-performance or mass-produced devices. On the other hand, function sharing is generally a poor design strategy for research devices and prototypes where debugging, adjustment and diagnosis are important.

Our work on function sharing is justified by at least two factors. First, modular, non-function-sharing devices are easier to design, understand and modify than function sharing devices. For this reason a useful approach to design would be to generate initial device descriptions in a modular, decomposed way but then subsequently to process the designs to make them inexpensive and reliable through the use of function sharing. Second, we are interested in innovative design, and function sharing is part of the perception of novelty, simplicity, or cleverness with respect to a mechanical device.

2.2 The key idea

The key idea that allows function sharing to be performed computationally is that most of the properties of a structural element in a design description are secondary and incidental to the properties that allow that element to implement its intended function. By recognizing and exploiting these secondary properties, neighboring elements can be eliminated from the design. For example, a modular non-function-sharing design of an automobile would include a ground wire running from the tail light to the battery. By recognizing that there is already an element (the automobile body) connecting the tail light to the battery, and that this element has the secondary property that it conducts electricity, the ground wire can be eliminated. Performing this reasoning requires a physical representation of the design, and an ability to recognize and exploit secondary properties of elements in this physical description.

3 Domain Description

As a domain for exploring function sharing, we have chosen mechanical devices whose schematic description can be expressed as a network of lumped-parameter idealized elements. The computer program that implements the function sharing procedure is further limited to devices that can be described with fluid-mechanical elements and mechanical-translational elements. Such devices include pressure gauges, accelerometers, force transducers, and pneumatic cylinders. We will call this domain *dynamic systems*. We have chosen the dynamic systems domain for four reasons. First, the schematic language for such devices is well-understood (generalized analog circuit language). Second, many devices in this domain can be described physically with two-dimensional geometrical representations. Third, the domain is of some engineering importance and interest. Fourth, the geometry of the devices is not generally constrained by packaging issues.

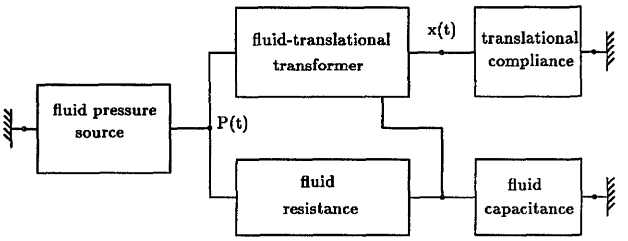

Figure 2: Schematic description of design

3.1 Describing devices schematically

In this paper, we focus on devices incorporating fluid-mechanical and translational-mechanical functional elements. These elements are fluid resistances, fluid capacitances, fluid inertances, translational inertias, translational compliances, translational dampers, and fluid-translational transformers. Figure 2 is a schematic description of a device to measure the rate of pressure change of the pressure source. The description consists of a network of five idealized functional elements. The pressure source specifies a pressure at the node labeled P(t). The fluid-translational transformer produces a force on the translational compliance proportional to the pressure drop across its other two terminals. The fluid resistance has a linear relationship between the pressure and flowrate across its terminals, and the fluid capacitance relates flow to change in pressure. The gross behavior of this network is that the displacement of the translational compliance will be proportional to the rate of change in the pressure source. This device can be thought of as an aircraft rate-of-climb indicator, if the pressure source is thought of as the atmospheric pressure surrounding the aircraft.

3.2 Describing devices physically

For a design to be realized, its schematic description in terms of idealized functional elements must somehow be implemented physically with structural elements. For our work on function sharing, we have chosen a two and one-half dimensional geometry to describe devices physically. In this representation, devices consist of a collection of structural elements (these can be thought of as design components like piston-cylinders or springs), which are in turn built from orthogonally connected rectangular-prismatic sections of material (these rectangular-prismatic sections are the primitive physical building blocks of the system). Figure 3 shows the physical description of a piston-cylinder structural element. Figure 4 shows the top view of the physical description of a rate-of-pressure indicator containing the piston-cylinder structural element. There is a structural element for each functional element in the schematic description in figure 2. Note that there are also two additional structural elements that correspond to the connection nodes in the schematic description. In this two and one-half dimensional geometry, Newtonian

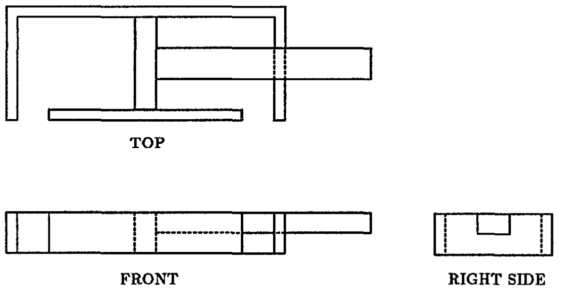

Figure 3: An example structural element represented as a collection of orthogonally configured rectangular-prismatic sections

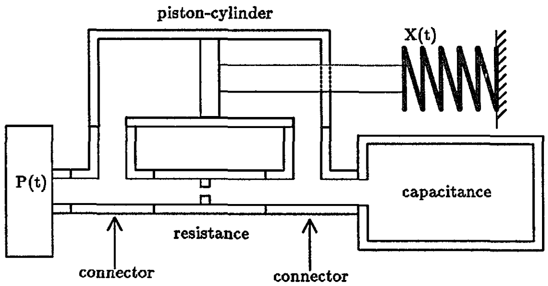

Figure 4: Physical description of a design approximating the behavior of the schematic description in figure 2

physics applies as if the device were fully three dimensional if one imagines the device to be sandwiched between two infinitely stiff and strong, frictionless plates. This particular physical representation was chosen to simplify the computational geometry problems while still maintaining the applicability of three-dimensional physics. Note that in our rate-of-climb indicator example, the pressure source and the translational compliance are considered part of the input and output environment of the device and therefore are not the target of simplification.

3.3 Problem definition

The input to the function sharing problem is both a physical and schematic description of a device with the correspondence between structural elements and functional elements specified. The output of the function sharing procedure is a physical description containing fewer structural elements. The objective of the procedure is to simplify the device.

4 Procedure

The function sharing procedure consists of three steps: 1) a structural element is deleted from the design; 2) physical features that can potentially implement the function of the deleted element are found; 3) modifications are made to the design to accentuate the desired properties of the features found in step 2. We describe each of these steps for the dynamic systems domain.

4.1 Deleting a structural element

The physical description of the design is represented as a collection of structural elements. The first step in the function sharing procedure is to remove one of these structural elements. Removal of a structural element from a design may cause some side effects. For example, removing a fluid element from a design may cause leakage. Removing a mechanical-translational element may cause parts of the design to become disconnected. Because of these side effects, the design must be repaired after the deletion step, requiring replacement of T-type connectors with straight or L-type connectors, replacement of L-type or straight connectors with plugs, and/or reconnection of disconnected regions of a design.

The deleted structural element corresponds to a functional element in the schematic description. This functional element can be thought of as being approximated in the physical description with respect to some geometrical reference point(s). For example, a fluid resistance is defined with respect to two points in the fluid flow. A translational inertia (mass) is defined with respect to a single point. So, for every deleted element there will be one or two corresponding reference points in the physical design description.

4.2 Recognizing alternative features

The second function sharing step is to find alternative features in the physical description, with respect to the appropriate reference point(s), that can potentially implement the function of the deleted structural element. We have approached this task as a computational geometry problem–that of identifying one of a set of known physical features that can approximate the relevant function. For example, fluid resistance can result from a narrow passage between two edges, a long narrow channel through a solid region, or an orifice in a plate. For each of these ways of implementing resistance there is a physical feature that could be potentially modified to achieve the resistive function. For example a path between two reference points that passes between two adjacent but detached edges could be resistive if a clearance were established between the edges. A path between two reference points that is obstructed by a solid wall could be resistive if a hole were punched in the wall. These relations constitute the function sharing knowledge base. The relations for fluid resistance are shown in figure 5.

4.3 Modifying features

Once the potentially useful features are found, the final step is to execute the modification operators associated with each feature. So, in the case of the fluid resistance, if the feature found by the recognition procedure were a path obstructed by a solid wall, the modification would be to punch a hole in the wall.

4.4 Control

Our implementation of the function sharing procedure leaves the control to the user. Specifically, the user selects an element to eliminate and chooses one of several modified designs as the starting point for another function sharing iteration. The control could also be automatic, although

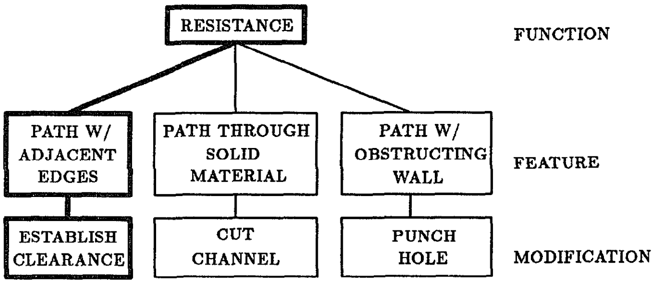

Figure 5: Organization of function sharing recognition and modification procedures

because there will in general be several design modifications for each deleted element, the worst-case number of designs generated by this procedure is exponential in the number of structural elements to be eliminated.

5 Example

This section illustrates the function sharing procedure for the rate-of-climb indicator with top views of the physical device description. In this example, the fluid resistance and fluid capacitance are both eliminated through two three-step function sharing cycles. Figure 6 shows a single branch of the possible outcomes of the function sharing procedure.

First, the fluid resistance is deleted, and the leaks repaired. The repair is accomplished in this case by simply replacing the T-type connector connectors with L-type connectors. Second, the feature recognizer finds a path between reference points A and B that passes between adjacent edges. Third, a clearance is established between the edges. This clearance makes the piston leaky; thereby eliminating the separate fluid resistance. To eliminate the fluid capacitance, first the fluid capacitance is deleted and the leak repaired. Second, alternative capacitive features are found with respect to point A. In this case the relevant feature is a cavity adjacent to A. Finally, the cavity is expanded by extending the piston length. By executing the function sharing procedure, a very modular, inefficient design is transformed into a simple and compact design.

6 Discussion

This work on function sharing as a design procedure fits into a larger project aimed at the general problem of generating design concepts computationally. In this section, we discuss several issues relating to function sharing and to the larger project.

6.1 Interpreting physical descriptions

The physical descriptions produced by the function sharing procedure can be thought of as parameterizations of a design description. In the case of a piston-cylinder, there are many possible parameters in the physical description that *may* be relevant to the design. The function sharing procedure is a way of identifying those parameters that

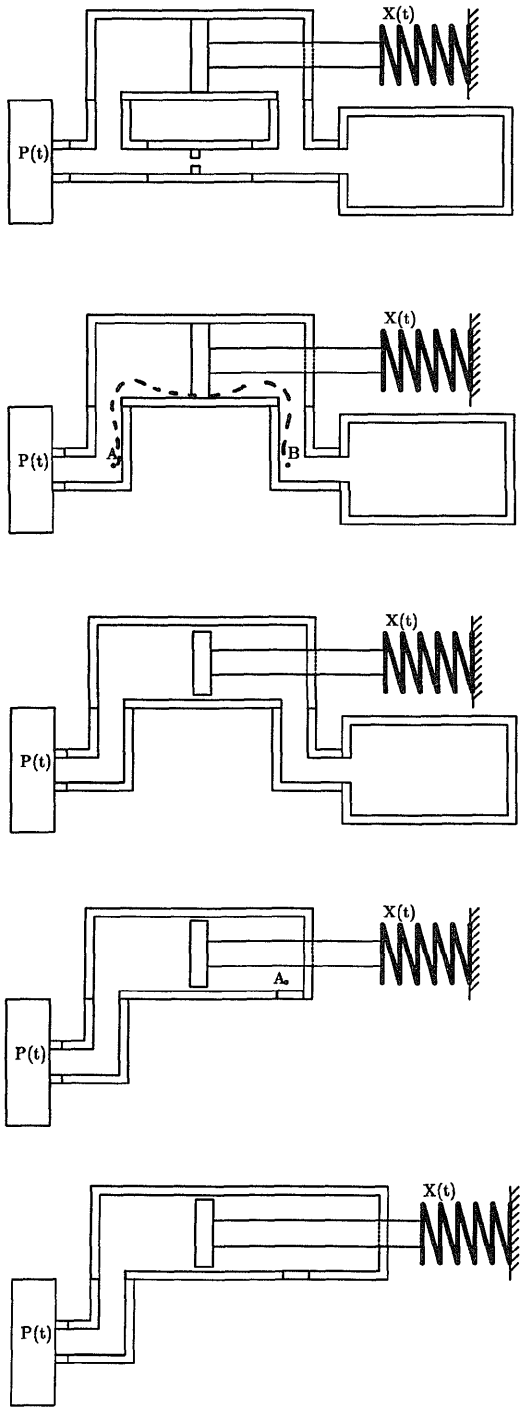

Figure 6: Simplifying the rate-of-climb indicator.

should be considered in the design. For example, a piston-cylinder is normally parameterized by the piston area and the stroke length. There are, however, many other parameters that relate to the element– among them the thermal conductivity of the cylinder wall, the size of the input and output ports, or the mass of the piston. After the function sharing procedure operated on the rate-of-climb indicator example, two of these extra parameters where identified as important– the clearance between the piston and cylinder and the volume of one end of the cylinder. The designer is alerted that the original design can be simplified if these parameters are considered when performing the detailed design and selecting dimensions.

6.2 Big picture

In other work [1], we have developed a technique for generating the schematic description of a device described by a relationship between input and output quantities. That work, paired with the function sharing procedure described in this paper, allows a computational system to generate an efficient physical description directly from a specified input-output relationship. This system would first generate a schematic description from a input-output specification and then, through the function sharing procedure, would generate an efficient physical description from the schematic description.

6.3 Implementation

The function sharing procedure has been implemented as a computer program. The program can simplify devices whose schematic descriptions consist of fluid resistances, fluid capacitances, fluid inertances, translational masses, translational resistances, translational compliances, and fluid-translational transformers; and whose physical descriptions are represented with the two and one-half dimensional geometrical language we have developed. The program performs all of the element deletion, feature recognition, and design modifications automatically, with the user specifying which element to eliminate at each step.

6.4 Novelty

One result of the implementation is the discovery that the unbiased application of our physical-feature-based function sharing procedure can yield some surprising designs. Figure 7 shows screen dumps of one outcome of the function sharing procedure applied to the elimination of a fluid capacitance.

7 Related Work

Several researchers have contributed to the work presented in this paper. Suh et al [2] propose a set of design axioms from which globally optimal designs should follow. These axioms suggest that functional elements be combined only when their properties can be controlled independently. Sussman [3] discusses the mapping between function and structure in mechanical devices, and points out the phenomenon of function sharing in a watch mechanism. Ishida et al [4] have developed procedures for detecting certain unanticipated functions (like leakage) in mechanical devices. This work was aimed at detecting

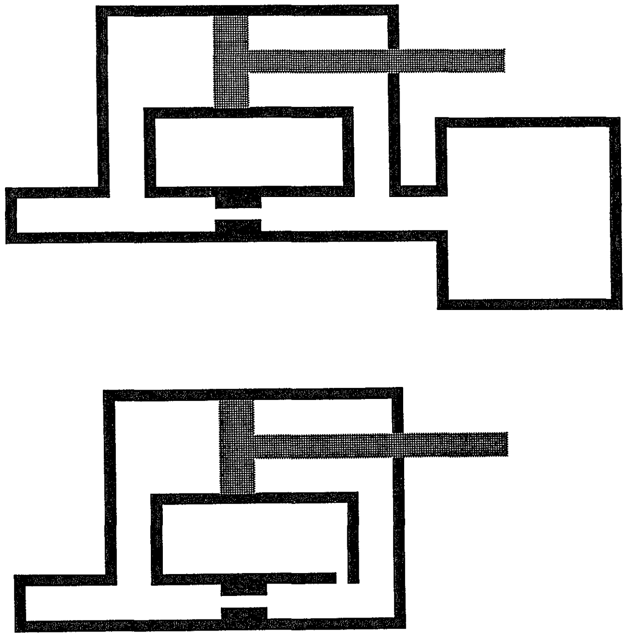

Figure 7: Novel design resulting from function sharing

harmful unanticipated functions, a task similar to detecting useful unanticipated functions. Hirschtick [5] developed a technique for recognizing features in a cross-section of an aluminum extrusion in order to suggest modifications to make the part more manufacturable. This work involved a feature recognition problem related to the one faced in function sharing.

8 References

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