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A NEW APPROACH TO STRUCTURE SHARING

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1 Introduction

Structure sharing means fulfilment of several functions by the same physical structure. The concept was popularised by [1], who used the term ‘function sharing’ to describe it. Structure sharing is an important concept in product design, and is often referred to using different terms such as combination of functions [2] or integrated structures [3]. They have been used consciously or unconsciously in making products more innovative as well as more efficient in terms of resources used. However, while the importance of these concepts has often been emphasised in literature, neither principles embodying them nor approaches and methods for supporting them, especially on computers, have been investigated in any depth.

Structure sharing is one of the four categories of sharing identified by [4]. While structure sharing has the positive benefit of decreasing the use of resources (e.g., amount of material, size, volume, weight, overall cost, etc) in making a product, it can also have the negative impact of decreasing its changeability (ease of adjustability, disassembly, repair, reuse and recyclability of parts). However, there are many areas, such as aerospace applications, where minimum use of resources is of prime concern, and structure sharing has widespread use.

The aim of this paper is to present a new, computational approach for supporting structure sharing in design [5]. The approach has been implemented into a software for automatically creating, and offering designers for evaluation, a variety of alternative solution principles as well as potential qualitative embodiments (termed here as conceptual structures) of sensors that can fulfil a given intended sensor functionality. These potential alternatives are structure-shared where possible. For instance, given the intended functionality of sensing a force using a voltage, the software suggests a host of alternative principles including that of using a surface area to develop a stress from the force, a piezo-electric effect for developing charge from that stress, and a capacitance for developing a voltage from the charge. It then generates several alternative conceptual structures for each of these principles, including one that uses the same piezo-crystal which has an area, piezo properties and dielectric properties to respectively activate the force-stress effect, piezo-effect and capacitance effect, all within the same component. Synthesis of solution principles was reported in [6]. This paper reports how these principles are automatically transformed into potential, structure-shared conceptual structures. The rest of the paper details the approach, its implementation and evaluation.

2 Related work

The sole work available on computational structure sharing is by Ulrich [1]. The approach starts with the intended functions of a product. It then develops a set of solution principles by combining a set of bond graph elements, and then replaces each element by a physical structure, which together form an embodiment. It then deletes some of these structures, and checks to see if the additional properties of the rest of the structures can fulfil the functions of the deleted structures. If this is possible, the component is definitely removed from the structure; otherwise it is reinserted. The program performs this test for all the structures in an embodiment, and the outcome is an embodiment that has improved structure sharing. The structure sharing procedure in this work is primarily geometry-based.

There are three potential problems of using this approach for our project, which aims to develop and offer designers for exploration a variety of alternative conceptual structures, structure shared where possible, that are essential for a solution principle to work. The first is that the approach operates at a geometric level while we need to operate at a more conceptual and generic level. The second is that it encourages structure sharing of a given concept along the lines of adaptive variation rather than generative variation [7], which makes it difficult to generate a wide range of alternative embodiments that allow choice between resource-effectiveness and changeability [4]. The third problem is the relative lack of computational efficiency and effectiveness of its generate-delete-test-(reinstate) loop, which would miss mutually dependent sharing options and require relatively more resources to run. The proposed approach is intended to alleviate all these problems.

3 Approach

In order to develop and evaluate the proposed approach to automated structure sharing, the domain of electromechanical sensors is chosen. The reasons include availability of comprehensive literature from which data can be collected, and the richness and variety of areas of engineering covered by sensor solution principles, which enable the approach developed to be generic and applicable to a variety of engineering domains.

Eleven cases, each pertaining to a separate family of sensors (having three to ten variants) all of which are based on the same principle, are analysed in order to identify the function, principle and conceptual structures of the sensors. This led to the identification of the key characteristics that can be used to develop the approach for developing alternative principles as well as conceptual structures of sensors to fulfil a given intended functionality, and where possible, make a conceptual structure structure-shared. Evaluation is done by comparing the existing conceptual structures of these sensors with those suggested by the approach, to test whether or not the ones suggested by the software include those available as well as new, structure-shared conceptual structures.

3.1 Data analysis and representation

Textual data on each of the eleven cases was collected from several books and catalogues into a single document for each case, which was then analysed. Data analysis consisted of identifying as to how each sensor works at the principle level (i.e., what effects are activated and how they fulfil the overall function) and at the embodiment level (i.e., what components are essential and how they fulfil the overall function for a given principle). This revealed, among others, that some preconditions must always be satisfied for an effect to be activated. The preconditions are existence of external variables, as well as characteristics of the components or interfaces of, or constraints on the structure of the sensor. These structures are described only by the attributes that they must possess in order to be able to activate the effects in the solution principle they represent, thus they are called *conceptual structures*.

For instance, in order to work, a piezo-electric sensor needs the force input on one of its surfaces. This input is converted into a stress by its surface area if the crystal is constrained against movement in the direction of the applied force. As a result, the crystal lattice is deformed, leading the piezo-crystal properties to generate a charge inside the material because of Piezo-effect. With two conductor plates placed on opposite surfaces of the crystal, the material shows capacitance behaviour due to its dielectric properties. A potential difference between the two plates is created due to Capacitance effect, which can be sensed by a voltmeter as a measure of the applied force (see Fig. 1).

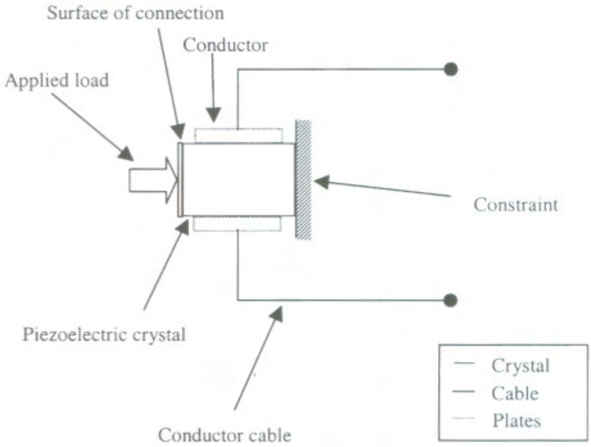

Figure 1. Conceptual structure of a piezo-electric sensor

Four constructs are developed to represent sensor concepts: variables, effects, components and constraints. A product function is represented as a transformation between input and output variables (e.g., a force input to be measured by an output voltage for the above sensor).

Figure 2. Representation of a solution principle

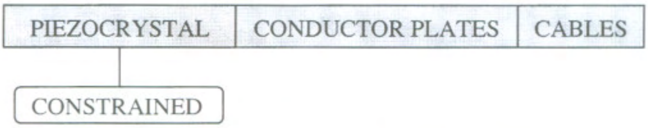

Figure 3. Representation of a conceptual structure

A sensor at the solution principle level is represented as a combination of effects that are strung together using their input and output variables. For instance, the piezo-electric sensor is represented as a chain of four effects as shown in Fig. 2. A sensor at the conceptual structure level is represented as a combination of components that are interfaced with adjacent components; some of the components may be constrained using appropriate constraints. For instance, the above sensor has a conceptual structure with three components and a constraint: a piezo-crystal that is constrained against movement, conductor plates that are interfaced with the piezo-crystal, and cables that are interfaced with the conductor plates (Fig. 3).

3.2 Algorithm

In order to enable generation of sensor solution principles for a given intended function, and possible conceptual structures for a given solution principle, two databases are devised. The first is a database of effects that links each effect with its input and output variables as well as the properties and constraints that are needed for the effect to be activated. For instance, the force-stress effect provides a stress output in response to a force input (variables); this requires a solid surface (properties) constrained against movement (constraint), see Fig. 4.

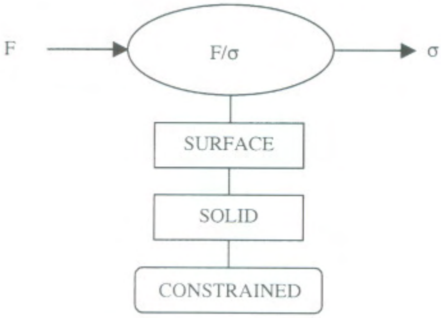

Figure 4. An effect linked to its I/O variables, and properties and constraints necessary

The second database links components, identified from data analysis, with their properties and allowable variables. For instance, a piezo-crystal component has the properties of a solid with surfaces having dielectric, piezo-crystal and low heat conduction properties, and has the ability to conduct force, stress, strain, electrical charge and voltage, in addition to being susceptible to stray magnetic and electrical fields. The existence of variables in the representation of intended functions and effects allows solution principles, which are combinations of effects, to be generated to fulfil a given intended functionality. The existence of properties in both the databases allows the effects in a given principle to be replaced by components, enabling automated synthesis of conceptual structures for the solution principle.

The algorithm for structure sharing has three steps: synthesis of solution principles for a given intended function, synthesis of initial conceptual structures for a given solution principle, and integration of a given initial conceptual structure into a structure shared one if possible.

Synthesis of solution principles

This part, already reported in [5], starts by developing a list of effects, from the effects-database, which have the same input variable as that of the intended function. For each of these effects, the respective output variable is then identified, and checked against the output variable of the intended function. If the two match, that effect can act as a solution principle for the problem. Otherwise, the output of the effect identified is set as the input variable for the next iteration, and the above procedure is followed again, which lead to stringing together of two effects. This procedure is repeated until the number of effects strung together exceeds a number pre-specified by the designer. The outcome of this stage is an exhaustive list of solution principles, each of which has the overall input and output as the intended function.

Synthesis of initial conceptual structures

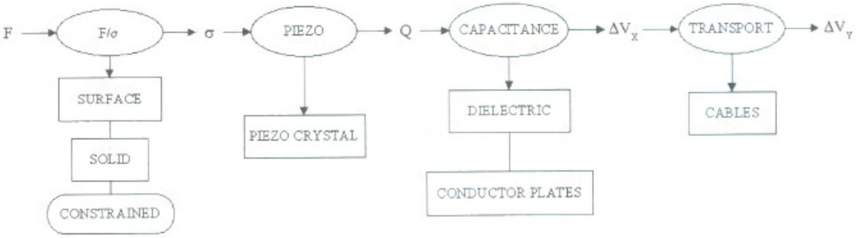

Figure 5. A solution principle (chain of ovals) linked to the properties and constraints necessary (boxes)

Synthesis of initial conceptual structures of a given solution principle is done by first identifying the list of properties and constraints required for each effect in the solution principle, see Fig. 5. The components database is then searched to find all possible component alternatives that can satisfy each of these properties. Each combination of components, one for each property necessary, forms an alternative initial conceptual structure, see Fig. 6.

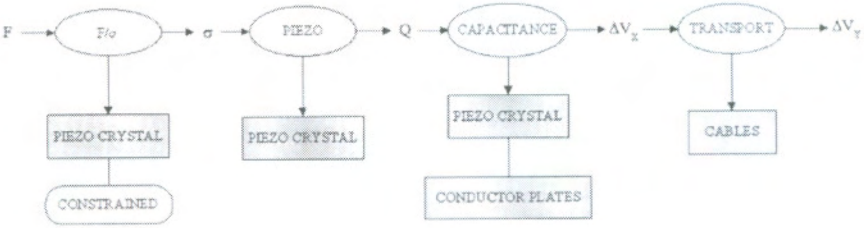

Figure 6. A solution principle linked to an initial conceptual structure (boxes in grey) and a constraint

Integration of the initial structure

An initial structure consists of a list of components, each of which satisfies only one of the properties required by the solution principle. Integration is done now by identifying each component in the initial structure that is chosen more than once, consolidating the copies into a single component when certain rules are satisfied, and propagating the constraints and interfaces accordingly. For instance, the initial conceptual structure in Fig. 6 shows that a piezo-crystal is used to activate the force-stress effect by constraining it against movement, another to activate piezo effect, and yet another, together with conductor plates, to activate capacitance effect. Also, the first crystal has to be adjacent to the second, while the second is to be adjacent to the third while also being adjacent to the conductor plates. Therefore, consolidation of the crystals is done by replacing these three crystals by one, and propagating constraints and interfaces to ensure that it is constrained against movement and remains adjacent to the conductor plates (which are adjacent to the cables). The structure shared final structure is shown in Fig. 3. The work is already implemented into a software demonstrator [5], where LISP is used as the implementation language.

4 Evaluation of the approach

Data collected on fifteen families of sensors are used to evaluate the approach. These include the eleven cases of data obtained at the beginning of the project as well as four additional cases collected for the express purpose of evaluation. The effectiveness of the approach is evaluated by using the program to generate a list of conceptual structures for each of these sensor cases. These are then compared with the data collected. The objectives have been to see whether the set of conceptual structures generated by the program (1) includes the conceptual structures existing in the data, and (2) contains other, novel, realisable structures.

The results of the comparison are shown in Table 1. The column headings are as follows. The 1st column indicates the type of principles involved in the cases considered, where each case considers a family of sensors. The 2nd and 3rd columns respectively specify the input and output required by the intended function of the sensors, where *tem-d.*, *pres.*, *volt.*, *curr.*, *temp.* and *disp.* mean temperature difference, pressure, voltage, electric current, temperature and displacement respectively. The 4th column specifies the number of components that the program was allowed to use to generate the conceptual structures (abbreviated as CS). Column five gives the number of alternative conceptual structures that were identified from the existing data. Column six gives the number of conceptual structures synthesised by the program in each case. Column seven gives the ratio of the number of structures proposed by the approach that are novel to those proposed that already existed in the data analysed. The 8th column gives the ratio of how many structures synthesised are structure shared to the total number of structures synthesised.

Table 1. Results

case type	**I**	**O**	**no. of comp. allowed**	**no. of CS from data**	**no. of CS synthesised by program**	**no.(new) / no.(exis) CS**	**no(SS) / no(syn) CS**
Piezo-elec.	force	volt.	3	1	1	0/1	1/1
Seebeck	tem-d.	volt	2	1	7	6/1	7/7
Resistance	temp.	volt	2	1	1	0/1	1/1
Resistance	pres.	volt	2	1	1	0/1	1/1
Capacitance	pres.	volt	3	1	1	0/1	0/1
Strain Gauge	strain	volt	3	1	1	0/1	1/1
Thermistor	strain	volt	3	1	1	0/1	1/1
Potentiometer	disp.	volt	3	1	1	0/1	1/1
Magnetostrict.	force	volt	3	1	1	0/1	1/1
Capacitance	disp.	volt	3	1	3	2/1	0/3
Self-Inductance	speed	volt	3	1	2	1/1	0/2
Nozzle-Flapper	disp.	pres.	3	1	4	3/1	4/4
Pressure	temp.	disp.	2	1	2	1/1	2/2
Ammeter	curr.	volt	5	1	16	15/1	4/16
Pressure	weight	pres.	2	1	2	1/1	0/2

Column seven shows whether the program can predict the conceptual structures of the existing sensors, which it does in each case, since the number of existing structures (Column five) is always the same as the denominator in the ratio in Column seven. In seven of the fifteen cases, it generates other, alternative conceptual structures for the sensors (shown by non-zero values of the numerator in the ratio). Except for three cases where even the existing conceptual structures are not structure shared, the program generates structure-shared structures in each case. This demonstrates the generality and power of the approach in creating structure shared designs whenever it is possible. The number of conceptual structure alternatives generated, however, are often few. However, since the number of components allowed (Column 4) is taken as the minimum that would generate any conceptual structures at all (except in Case 14); increasing this would generally increase the number of alternative conceptual structures. For instance in Case 14, using the minimum allowable number of components of 4 would have given four alternative conceptual structures.

There are a number of cases where the conceptual structure alternatives generated by the program are quite interesting. For instance, in the Ammeter case, a structure generated is better structure shared than the existing design. The existing design uses a bar to transmit torque generated in a coil by the input current, and a separate spring to provide the spring action necessary. In contrast, an alternative, novel structure, suggested by the program, uses a single bar to do both the transmission and the spring action, thereby reducing the number of components necessary.

5 Discussion

The approach presented is a crucial departure from the only available approach to computational structure sharing [1]. The existing approach starts with the intended functions of a product, develops a principle as a combination of effects, and replaces them by elementary structures for each effect. It then deletes some of these structures, and checks to see if the additional properties of the rest of the structures can fulfil the functions of the deleted structures. In other words, the approach progresses through functions to principles to structures to properties, in order to achieve structure sharing.

In contrast, the approach proposed here starts with the intended functions, and synthesises solution principles as combinations of physical effects that satisfy these functions. It then identifies the properties essential for fulfilment of the effects in a principle, and from these creates possible conceptual structures for the principle by combining elementary structures that have the required properties. Finally, it compares the elementary structures in a conceptual structure to identify whether the same elementary structure is used more than once in the conceptual structure. It that case, all these elementary structures can be replaced by just one of them which would now satisfy all these functions. In other words, the approach progresses from function to principles to properties to structures.

Apart from having the level of representation appropriate for the present task, there are three potential advantages of the approach proposed over the earlier approach. The first is that while the earlier approach encourages structure sharing of a given concept along the lines of adaptive variation, the new approach encourages the more desirable simultaneous generation of alternative conceptual structures, allowing choice between resource-effectiveness and changeability. The second advantage is its relative efficiency over the earlier approach. While the earlier approach may have to carry out an inefficient iteration between deleting structures, checking ability of other structures to fulfil the functions of the deleted structures and making up for the deleted structures, the new approach allows all this to be done in a direct, non-iterative way. The third advantage is that the new approach makes it easier to identify potential side effects in a conceptual structure, another goal of this project [5, 8], since it connects physical effects to elementary structures using properties necessary.

6 Conclusions and further work

The main conclusions are:

- Structure sharing is an important principle for design for effective use of resources, but little is currently available for supporting it during design. While structure sharing increases effective use of resources in a product, it can decrease its changeability. It is one of four kinds of sharing that provide various degrees of trade-off between these two goals.

- A computational approach has been developed that achieves structure sharing following reasoning through functions, principles, properties and structures. The approach encourages development of alternative concepts, is efficient in its directness, and allows easy detection of side effects. The approach has been tested using a range of sensor designs; existing as well as new conceptual structures for these sensors have been suggested by the approach.

Further work involves supporting evaluation of conceptual structures, and development of physical embodiments for these structures.

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