A TOOL FOR AUTOMATED SYNTHESIS AND SIDE-EFFECTS DETECTION IN SENSOR DESIGNS

Amaresh Chakrabarti[1,a], Riccardo Regno[2,b], Biplab Sarkar[1,c] and Srinivasan V.[1,d]

[1] *IDeaS Lab, Centre for Product Design and Manufacturing, Indian Institute of Science Bangalore – 560 012, India.*
[2] *Bridgestone Inc., Rome, Italy.*

Email: [a] *ac123@cpdm.iisc.ernet.in,* [b] *riccardo.regno@gmail.com,* [c] *biplab@cpdm.iisc.ernet.in,* [d] *srinivasan@cpdm.iisc.ernet.in*

Side-effects in a system are defined as effects which affect the intended working of the system. Unforeseen side effects are often blamed to be the cause of avoidable accidents in the history of engineering, the consequences of which are often disastrous. This research explains the development and evaluation of a computer-based tool to: synthesize alternative solution principles from a given sensor function, synthesize alternative conceptual structures for each solution principle and detect side-effects in these designs.

Keywords: Sensor, side-effect, synthesis, solution principle, conceptual structure.

1. INTRODUCTION

Engineering design is a process of transforming a set of requirements into a set of descriptions of an artefact with which to fulfil those requirements [1]. The process can be broadly divided into four stages: planning and task clarification, conceptual design, embodiment design and detail design [2]. Our focus here is on conceptual design.

Conceptual design is defined as the stage in which solution principles are developed [2]. Compared to other stages, conceptual design offers greater fluidity, flexibility and scope for striking improvements [3]. A lasting and successful solution is more likely to spring from the choice of the most appropriate principles than from exaggerated concentration on technical details [2]. On an average, about 80% of the cost of a product over its total life cycle is committed during its conceptual design stage [4].

Physical laws and effects (henceforth called effects) are principles of nature governing change [5]. They provide important information for invention and development of artefacts [6], by supporting creativity [7, 8]. Various researchers [8, 9] used effects for designing technical systems. Knowledge of effects helps identify possible trouble areas in early stages of product development; in the absence of this knowledge, existence of significant, unexpected effects are often discovered late in the testing stage [10].

Side-effects in a system are defined as effects which affect the intended operations of the system [11]. Unforeseen side effects are often blamed as the causes of avoidable accidents in technical systems, the consequences of which can be disastrous. Side-effects are either identified from experience or field tests after the development of the product; these can be prone respectively to misjudgement and cost [11]. In several avoidable accidents which were due to unforeseen side-effects, designers often overlooked the effect of side-effects in their design [12, 13]. Hence detecting side-effects need more systematic support during the design process itself [11].

Research into Design — Supporting Sustainable Product Development. *Edited by* Amaresh Chakrabarti
Copyright © 2011 Indian Institute of Science, Bangalore, India
:: *Published by* Research Publishing
ISBN: 978-981-08-7721-7

Sensors are devices for detecting or measuring physical quantities. Sensor designs can be seen as combinations of elementary devices and effects [9]. The issue of side effects is particularly relevant for sensors, as sensors must often provide precise measurements, and side effects limit their precision. Comprehensive literature on sensors exist [14], including data on the side effects from which sensors suffer. A computational support for conceptual design of sensors could enable fast and a comprehensive exploration of alternative designs. The overall objective of this work is thus to develop a computer-based support for automated synthesis of sensor designs and detection of potential side-effects in them.

2. LITERATURE SURVEY

2.1. Literature on synthesis of solution principles and conceptual structures

Vast literature exists on conceptual design synthesis; we focus on those that make explicit use of effects. In [2], designing is proposed to be carried out through these abstraction levels: planning and task clarification, conceptual design, embodiment design and detail design. The outcomes of these respectively are: requirements list; principle solution; preliminary and definitive layout; and product documentation. From requirements, functional structures are established which are used for identifying working principles and structures. The latter two are combined to create principle solution variants. A principle solution variant is detailed by adding form, material and parts, to constitute a definitive layout. Product documentation includes drawings, bill-of-materials and other instructions. In [9], a framework is proposed to: (i) support formulations of device functionality, (ii) generate solution principles to fulfil these, and (iii) embody and envision these principles. A representation is developed for sensor designs: functions are described using input-output; solution principles as combination of effects, where inputs or outputs are physical quantities — effects are combined to take the output of an effect as an input to another and so on until the function is satisfied. An automatic search algorithm for synthesizing solution principles is proposed. In [15, 16], conceptual structures are also embodied, automatically, from the solution principles.

In [17], the approach has these levels: requirement, functional, physical principle and embodiment. In the requirement level, the preconditions of the design and its to-be properties are specified. At the functional level, functions describing product behaviour at a non-physical level are specified. At the physical principle level, a physical solution is described in terms of its effects and geometric information such as effective lines, surfaces and spaces. At the embodiment level, geometric information of points, lines, surfaces, design features, parts and assemblies are added. Each abstraction level is governed by a general problem-solving cycle: define problem, and, find, describe, evaluate and select solution. In [8, 18], an approach prescribes synthesis of technical concepts to follow these levels: function, physical laws, basic schemata and embodiment. Function is taken as an input-output transformation, where input and output are physical variables; the input is connected to the output by chaining physical laws. Basic schemata consist of geometric elements (point, line, surface, volume 'wirk' elements, and connecting structures) and physical quantities, and enable connection between physical laws and structure of the system. At the embodiment level, the basic schemata are realised by components.

2.2. Literature on side-effects and related areas

Activation of effects requires relevant input and context parameters [11]. These can arise from the: intended I/O and context parameters in the solution principle; embodiment having additional context parameters; working environment of the system; and misuse/abuse of the system. Identification of side-effects involves detecting available inputs and context parameters in the system and its environment, and identifying which effects could be activated as a result. Activation of these effects generates further outputs, and enables further effects to be activated. Some of the outputs from these effects would be of the same kind as those in the solution principle; these are the side effects on the system. Based on the origin of input and the direction of propagation of a side-effect, the side-effect categories identified in [11] are: *feed-forward effect* with intended system input; *feed-forward effect* with unintended system input; *feed-back effect* with intended system input; *feed-back effect* with unintended system input; effect with external input. An approach to detect side-effects is also proposed, but not supported on computers.

Conformability Analysis (CA) [19] is a methodology for predicting potential process capability problems in component manufacture and assembly. The methods link process variability risks with design acceptability and likely failure costs in production/service.

Design for Quality Manufacturability (DfQM) [20] supports systematic analysis of product components that have high probability of failure during assembly. The failures are based on: influencing factors and factor variables. These factors are introduced into "error catalysts" which describe undesirable factor variable conditions; the prevailing level of each factor variable is used by an error catalyst function to create a likelihood estimate of each specific defect. Booker *et al.* [21] propose Design for Assembly Quality (DfAQ) — to identify product components that have high assembly process risk factor and failure costs. This analysis allows designers to understand and quantify the effects of shape, features and other characteristics of a part during assembly operations, and anticipate the difficulties the product constituting the part will face during assembly.

Poka-yoke technique [22] for eliminating product defects related to human errors is based on six error-proofing principles: elimination, replacement, prevention, facilitation, detection and mitigation. Ideally, error-proofing should be considered during product development itself in order to maximize opportunities in preventing errors. Hazard and Operability Analysis (HAZOP) [23, 24] systematically divides a system, equipment, or process into a series of nodes for identifying potential hazards. HAZOP can be used to predict hazards and operability problems early in the Design for Safety cycle or on a released product. The technique can be used for both hardware products and procedures.

Design Failure Modes and Effects Analysis (DFMEA) [25] allows a design team to document during design what they know or suspect about a product's failure modes and their likely risks (by multiplying severity, occurrence and detection ranking), and use this information to mitigate the causes of failure. Since FMEA is dependent on the team that examines product failures, it is limited by their knowledge of previous failures. As a top-down tool, FMEA may identify only major failure modes in a system, and may not discover complex failure modes involving multiple failures within a subsystem [25]. What-If Analysis [26] is a brainstorming-based approach to identify situations that could produce an undesirable consequence. An experienced team familiar with a process can voice concerns that begin with "What If" about possible undesired events in the process starting from raw material to the final product. This enables identification of possible accident situations, their consequences and existing safeguards, and generation of alternative suggestions for risk reduction. The approach can be applied to any process, contingency planning and accident analysis. Anticipatory Failure Determination (AFD) [26] is a failure analysis method to help identify and mitigate failures. AFD involves: formulation or inversion of the problem; search for solutions or methods to produce failures; and verification of availability of resources to cause the failures.

2.3. Summary and Specific objectives

The literature on side-effects reveals that little effort has gone into: detection of side effects at early design stages, and supporting automated detection on computers. The specific objectives of this research are to develop a computer-based tool that combines:

(a) Synthesis of alternative solution principles from a given function
(b) Synthesis of alternative conceptual structures from each solution principle
(c) Detection of side-effects for the principles and associated conceptual structures.

We provide an overview of results related to objectives (a-b), previously published in [9, 15, 16], and detailed results for objective (c) which is the primary focus of this paper.

3. RESEARCH METHODOLOGY, RESULTS, AND EVALUATION

Existing sensors are used to develop and evaluate this work; research steps are as follows.

3.1. Data collection and analysis

The sensors are identified from [14]. Data is collected on how each sensor works — what effects and components are used (i.e. its solution principle and conceptual structure), and what effects are found undesirable (side-effects). Eleven families of sensors, each based on different principles, are used. We take *variable* as a quantity the variation of which is used or measured by a sensor. It is either an input or an output of an effect. Most variables are associated with energy and are transitional, e.g. pressure, velocity, charge, etc., while some can be properties of components that may undergo change due to an effect. A *component* is an individual physical element in a sensor and is defined here in terms of its properties. For instance, a ferromagnetic bar has the property of a bar i.e. a prevalent dimension and an unspecified cross-sectional area. In addition, this bar is made of a ferromagnetic solid material. Its surface conducts electricity and heat. Therefore, a ferromagnetic bar is described by these properties: bar, ferromagnetic, solid, surface, electrical conductor and heat conductor. *Constraints* are relationships among components, or between a component and the reference frame. These relationships can be geometric, spatial or among component properties. For instance, a constraint for a structure may be that two of its components cannot move relative to each other.

The data is structured using these fields: name of the sensor; Input-Output; working of the sensor; potential side-effects; constraints; and schematic diagram. For example,

Name: Piezoelectric transducer; *Input*: Force; *Output*: Electrical potential difference

Working: The transducer takes force as input on one of its surfaces. This force is converted into stress by the surface area of the crystal. If the surface area is constrained to be immoveable along the direction of the load (F/σ effect), the crystal lattice is squeezed and deformed, causing the piezoelectric crystal properties to generate a charge inside the material (PIEZO effect) which depends on the orientation between the stress and the lattice crystal. Two conductor plates are placed on opposite surfaces of the crystal. The crystal material has dielectric properties. So it acts as a capacitor (CAPACITANCE effect). The electrical potential difference between the two plates are collected and transported by two conductor cables (TRANSPORT effect).

Side-effects: Generation of heat in the crystal and conductor plates due to DISSIPATION and, JOULE'S effect, respectively; generation of electrical and magnetic field in the crystal, cables and environment (LEAKAGE effect); noise in the form of signal pulse due to TRIBOELCTRICITY inside the cables, if the cables are coaxial; change in electric potential due to leakage of the charge due to CONDUCTION effect.

Schematic diagram: (see Figure 1)

3.2. Development of representation

Fundamental to the understanding of the functioning of a sensor are the effects and how they are activated. For activation, effects require certain variables, properties and constraints to be present in

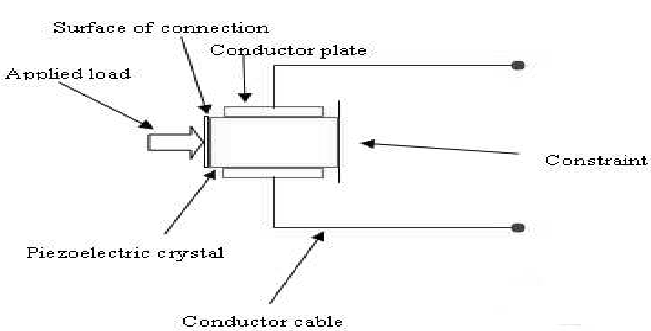

Figure 1. Schematic diagram of piezoelectric transducer.

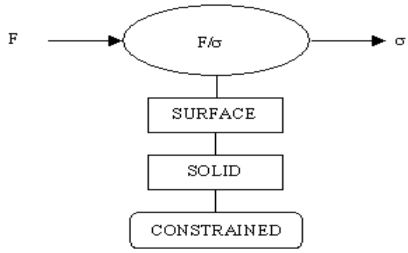

Figure 2. Conceptual structure of Force-stress effect.

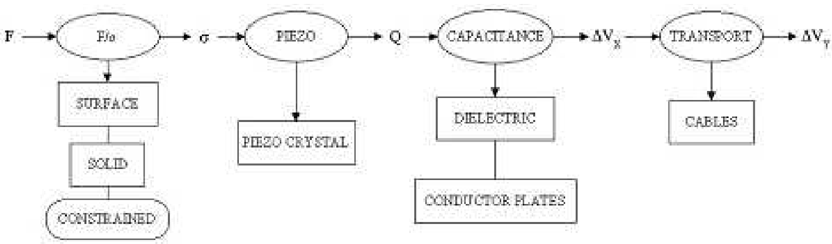

Figure 3. Functionality graph of Piezo-electric Transducer.

the physical components or their relationships to the environment. For example, take the force-stress effect, shown as oval in Figure 2, which coverts a force input (variable) into a stress output (variable). It requires a surface (property) on which to apply the force, a solid (property) adjacent (constraint) to the surface to experience this force, and it must be constrained (constraint) against movement in the direction of the force to be deformed by the force. In the figure, arrows point to/from variables, boxes describe properties, round-edged boxes represent constraints (other than adjacency), and links among these represent adjacency constraints. For example, the link between the oval and 'surface' (Figure 2) means that the input force is applied on the component having this surface; the link between 'solid' and 'constrained' means that this constraint is applied to the component having 'solid' property.

Sensor data is represented in two diagrams: a *functionality graph* and an *effects graph*. The *functionality graph* of a sensor describes all the intended effects that constitute its solution principle, and all the variables, properties and constraints that are essential for each of these effects to be activated. In Figure 3, the functionality graph of the piezo-electric transducer is shown. The solution principle is shown as a chain of effects connected through their inputs and outputs; each effect is linked to the properties and constraints required for its activation. The graph implies that this sensor works by activation of four effects: force-stress effect generates a stress in response to the input force, piezo effect generates electrical charge in response to this stress, electrical charge is converted to electric potential difference (voltage) by capacitance effect, and transport effect transports this electric potential difference (voltage) to another location.

An *effect graph* (Figure 4) shows the effects, intended and unintended. It also displays the connections between the various effects activated and the activated variables. The graph is divided into a number of parts. Dashed lines mark component boundaries. These components together form the conceptual structure of the sensor. Each component is visibly indicated on the top of the graph by a component name. On the left side of the graph, the input variable is identifiable, from which the intended chain starts. A double arrow with thick line indicates the intended chain — a sequence of effects alternated by activated variables that connects the given input to the desired output. Effects that are dependent on the interfaces of components are shown across the components' boundaries.

3.3. Effect and component database

The effects constituting the sensors are stored in a *database of effects*. Each record in the database has these fields: effect-name, necessary-input, inputs, outputs, un-intended outputs, constraints and

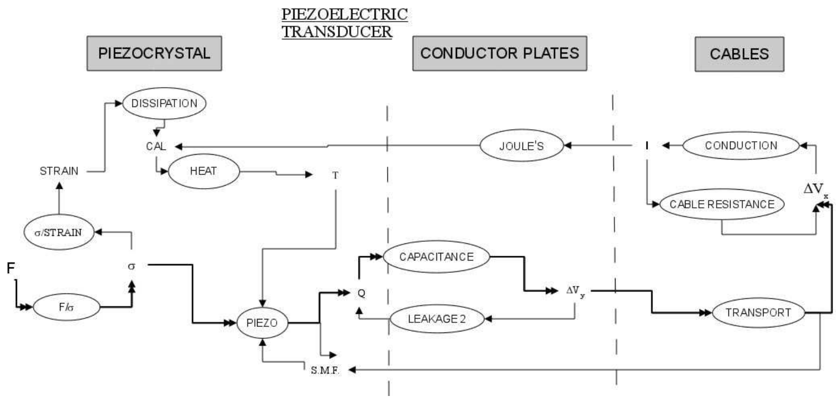

Figure 4. Effect graph of a Piezo-electric Transducer from literature.

affected-by variables. There are currently fifty records in this database. The components identified from the conceptual structure of the sensors used as cases are stored in a *database of components*. It describes each component and its properties. Each record has the following fields: component-name, properties and allowable-variables. There are currently twenty entries in this database.

3.4. Development of reasoning algorithms

There are three algorithms, for automated: (i) synthesis of solution principles for a given intended function, (ii) synthesis of conceptual structures for a given solution principle and (iii) detection of side-effects for a given conceptual structure.

The algorithm for the synthesis of solution principles needs as argument: required input and output for the sensor; maximum number of effects to be used in a solution principle; maximum number of components that can constitute a conceptual structure. Synthesis starts by identifying a list of effects, from the effect database, which have the same input variable as that of the intended function. For each effect, the respective output variable is identified, and checked against the output variable of the intended function. If the two matches, that effect can act as a solution principle. Otherwise, the output of the effect identified is set as the input variable for the next iteration, and the procedure is repeated, leading to stringing together of effects. This is done until the number of effects strung together exceeds the maximum number of effects. The outcome is an exhaustive list of solution principles, each with the overall input and output as the intended function.

Synthesis of conceptual structures for a given solution principle starts by identifying the list of properties and constraints needed for each effect in the solution principle. The component database is then searched to find all possible component alternatives that can satisfy each of these properties and constraints. Each combination of components, one for each property needed, forms an alternative initial conceptual structure. A conceptual structure has a list of components, each of which satisfies only one of the properties required by the solution principle. In structure sharing [15, 16] the same structure performs more than one function, and is used in the synthesis of conceptual structures if the properties and constraints required by multiple effects in a solution principle can be provided by a single component.

After having developed the conceptual structures, side effects detection begins. We explained before that each effect requires some properties, constraints and variables to be present in the conceptual structure to be activated. The detection process runs multiple iterations, starting with the inputs and effects already activated, to explore if more effects from the database can be activated using the variables, properties and constraints available from the effects already activated. The variables, properties and constraints of the components of the solution principle are examined, and activated variables are flown from one component to the others. The flowing of variables into a component may

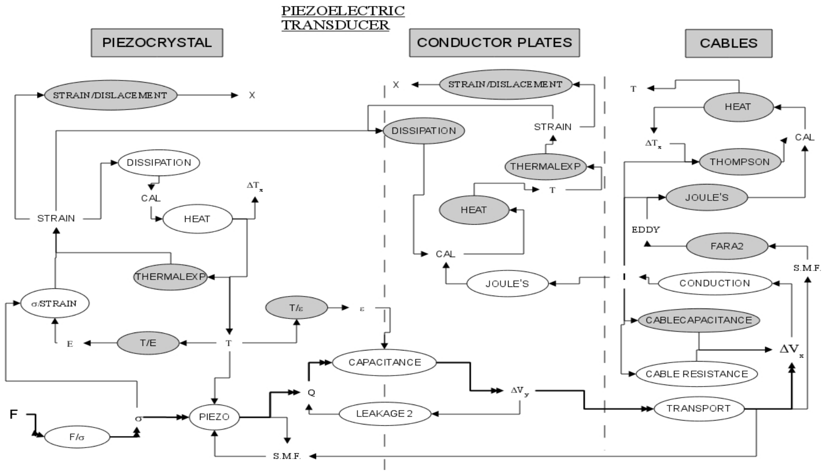

Figure 5. Effects and Side-effects in the Piezo-electric Transducer.

Table 1. Comparison of results with existing data.

Type of transducer	Input	Output	Max Comp allowed	Effects from literature (A)	No. effects detected (B)	Ratio (B-A)/A
Piezo-elec.	Force	volt	3	11	24	2.18
Seeback	TempDiff	volt	2	11	21	1.90
Resistance-thermo	Temp	volt	2	11	25	2.17
Resistance-Pressure	Pressure	volt	2	12	27	2.25
CapacitancePressure	pressure	volt	3	9	17	1.89
Strain Gauge	strain	volt	3	15	31	2.06
Thermistor	strain	volt	3	9	14	1.50
Potentiometer	disp.	volt	3	15	30	2.00
Magnetostrict	force	volt	3	9	25	2.70
Capa-displacement	disp.	volt	3	10	26	2.60
Self-Induct	speed	volt	3	4	9	2.25

activate new effects, if required properties and constraints are met. Thus, new variables and effects are activated and the iteration continues until all such possibilities are found.

3.5. Implementation, results, testing and evaluation

The approach, from synthesis of solution principles to detection of side-effects, has been implemented in a computer program using Common Lisp. The side-effects detection program is evaluated by comparing the number of effects (intended and side-effects) used/detected in the solution principle from the literature and the number of effects for the same solution principle as predicted by the program. Eleven sensor-cases are used. The output from the program contains an exhaustive list of possible alternative solution principles and conceptual structures that can be generated from the databases of effects and components to satisfy a given sensor function. Results in [15, 16] show that for most of the sensors, the program synthesizes a variety of alternative solution principles and conceptual structures, in addition to the existing ones from literature. The program currently uses effects and components only from the information collected (see Section 3.3). If a more comprehensive database is used, a larger set of alternative solution principles and conceptual structures can be synthesized. Currently the results need to be analyzed by the designer, who must construct the effects graph from the program output, for easy comparison with the data collected from literature. By comparing the effects graphs, the number of new effects that have been identified as potential side-effects can be seen. An example comparison can be done between Figure 4 and Figure 5 for one such conceptual structure that realizes the same solution principle. The additional side-effects detected by the algorithm are shown using darker shades in Figure 5. In Table 3.1., the results of comparison for the eleven sensor-cases are shown. In all the cases, the total number of effects (intended and side-effects) in the same solution principle as predicted by the algorithm is more than the number in the literature (Columns 5-6), accounting for new side-effects that may arise in addition to those found in the literature (Column 7).

4. SUMMARY AND FUTURE WORK

A computer-based tool for: synthesizing alternative solution principles from a given function and alternative conceptual structures for each solution principle, and detecting side-effects from these are developed and validated. Current implementation applies only to SISO systems. Extension to MIMO systems and quantitative detection and prevention of side effects are planned for the future. Since the approach uses the concept of flow of energy we can limit it to systems that can be expressed as lumped models [27].

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