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AN APPROACH TO AUTOMATED SYNTHESIS OF SOLUTION PRINCIPLES FOR MICRO-SENSOR DESIGNS

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conceptual design, solution principles, automated synthesis, functional reasoning, sensors

1 Introduction

Literature on sensor designs suggests that much of the process of designing sensors revolves around generating a design concept, identifying its potential behavioural problems, and trying to fix these problems [Sessler, 1994]. This is especially true for the relatively new sub-area of micro-sensor designs where, due to lack of experience, the generate-evaluate-modify cycle can be especially time-consuming and costly. It appears that this process could be much improved by providing a framework where the designer could be supported to develop alternative formulations of the device's functionality, and to generate and explore alternative solutions at various levels of detail. However, no such framework presently exists in this area, although Chaplin et al [1995] goes some way in this direction for macro-sensor designs.

Unlike the area of micro-sensors, the area of macro-sensors presents a wide variety of existing designs which can be seen as combinations of a finite set of common principles. This means that if these principles can be identified, represented formally and combined in a systematic way on computers, this will allow us to automate, for a wide range of sensor design problems, the generation of a wide variety of alternative solution principles and their possible physical embodiments. As these principles apply also to micro-domain, these and their embodiments could be used for micro-sensors too, subject to their scalability to the micro-domain.

The goal of this research is to support the essential generate-evaluate-modify design cycle, by devising a framework for micro-sensors to support alternative formulations of required device functionality, to automatically offer a range of alternative solution principles to achieve this functionality, and to support embodiment, envisionment and modification of these principles. In this paper, we tackle the first two of these objectives: (i) how alternative formulations of required functionality can be supported, and (ii) what representation and reasoning are required to automatically offer a range of alternative principles to achieve that functionality.

2 Approach

The essential idea, as illustrated in [Chakrabarti, 1995, Kiriyaama & Johnson, 1995], is that a wide range of sensors designs can be seen as combinations of common elementary devices and effects. Therefore, if these elementary devices can be systematically identified and suitably represented so that they can be combined automatically to suit a specified functionality, this

will offer a range of alternative solution principles, where a solution principle is defined as a causal network of elementary devices. This entails three major tasks: (i) identify elementary devices to develop a database of elementary devices, (ii) develop suitable representation and algorithms, and implement them into a system, and (iii) test and evaluate the system.

2.1 Developing a Database of Elementary Devices

In order to identify the knowledge needed for developing a database of elementary devices and effects, we analysed a range of existing designs to identify the elementary devices they shared. There are three sources of knowledge about elementary devices: **definitions** which can be used to measure any of the parameters they deal with (eg, mass is the product of volume and density: if a larger mass would help amplify a certain effect, this could be achieved by either increasing the volume of the object which is acting as a mass, or the density of the material from which it is made); **physical principles** which can be used in a number of ways in a device (such as using Newton's laws of motion for measuring mass, force or acceleration); elementary **devices or effects**, each of which makes use of one or physical principles.

2.2 Representation and Search Algorithm

Although there have been several attempts to provide general support to generation of solution principles [Roth, 1970; Chaplin et al, 1994; Malmqvist et al, 1996], most support synthesis only passively, either by supporting function decomposition followed by a choice by the designer of possible effect alternatives from a database, or by providing functionally indexed catalogues of physical effects which can be used by designers to create solution principles. A notable exception is the program developed by Ulrich and Seering [1989]; it regards a sensor function as a transformation between an input signal and an output message, and can compose a set of lumped-parameter elements to automatically generate schematic single input/output principles to satisfy this function. However, even this approach only partially addresses the general problem of synthesising sensor solution principles. We feel that a sensor function, and the elementary devices that can be composed to form its solution principles, need to be represented in terms of the input signal and output message as well as the media in which these are to be sensed. Without this essential expansion in representation and an expansion of the scope of synthesis to multiple input/output systems, a large portion of potential solution principles cannot be generated by the automated synthesis process.

The system is conceived here as fitting together a number of elementary **devices**. Each device takes as its input a **signal** in a given **medium**, e.g. an acceleration or a voltage, and produces an output signal whose **message** is some function of the input signal, and whose medium may be the same as, or different to, that of the input signal. For instance, a differentiator device could take as its input a voltage which represents a velocity signal, and gives as output an acceleration message (which is a derivative of velocity with time), also given in the voltage medium. So, both the input and output of this device is a voltage, but while the input voltage represents velocity, the output voltage represents acceleration. Figure 1 shows a device, inertia, which expresses an input acceleration (signal) in terms of an output force (message).

acceleration-> **inertia** -> force

Figure 1. An example of an elementary device: inertia to measure an acceleration in terms of a force

Figure 2 uses the principle of a capacitance-based accelerometer, to illustrate how the above concept of elementary devices can be used to represent the solution principle of a sensor

device. This principle uses five elementary devices: an **inertia** to provide a force representing the input acceleration, a **spring** to provide a displacement representing its input force, a **position-area** device to provide an area-change representing its input displacement, an **area-capacitance** device to provide a capacitance-change representing the input area-change, and a **capacitance-voltage** device to provide a voltage representing its input capacitance-change. The overall effect is an output voltage message representing the input signal, acceleration.

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acc-> inertia -force-> spring -posi.-> posi-area -area-> area-capa -capa->capa-volt -> volt
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Figure 2. An example of a solution principle: using five devices to sense acceleration in terms of a voltage

The search algorithm is adapted from the Functional Synthesis algorithm [Chakrabarti, 1991]. Presently, it uses exhaustive search and should find any solution to the problem which exists, given the known devices and a limit to the number of devices that can be strung together. The process of attaching a new device to a current output stream firstly involves finding the next device in the list that accepts the relevant medium as its input. The device then returns the new medium type and an expression of the process applied to the signal. The system is implemented on LispWorks (trademark of Harlequin Ltd, UK) package, using Common-LISP.

2.3 Evaluating the System: Accelerometer Design Case Study

The system was tested by (i) running it to generate solution principles for sensing acceleration in terms of voltage, as was set in a case study involving a team of designers from industry and academia to design innovative micro-accelerometers [Burgess et al, 1995], and then (ii) comparing these principles with those that the designers considered. We wanted to check if the system could suggest the principles which the designers considered, and more importantly other interesting principles which they did not, which would illustrate the system's potential to expand designers' thinking by widening the range of alternatives to be considered. The design task was to transform an input acceleration into an output voltage, using, from a database of eighteen elementary devices, at most six in a single solution. The total number of solutions generated was eight (Figure 3); this included the three (the fifth, sixth and seventh ones from the top in the Figure) which the designers considered, as well as several interesting others (eg, one that uses thermoelastic effect, the top one in Figure 3, to transform stress into voltage) that were considered neither in this case study nor in the research cited in literature.

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acc-> inertia -force-> force-stress -stress-> thermoelastic -> voltage
acc-> inertia -force-> force-stress -stress-> piezoelectric -> voltage
acc-> inertia -force-> spring -position-> strain-gauge -resistance-> resist-volt -> voltage
acc-> inertia -force-> spring -position-> tunnelling -current-> current-volt. -> voltage
acc-> inertia -force-> spring -position-> capa-distance -capa.-> capa-volt -> voltage
acc-> inertia -force-> spring -posi.-> posi-area -area-> area-capa -capa.->capa-volt -> volt
acc-> iner -force-> spring -posi-> tunnel -curr.-> widieman -rotation-> wurthiem -> volt
acc->iner-force->sprng-posi-> tunnel-curr-> peltier-temp-> resi-temp-resi-> resi-volt->volt
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Figure 3 The solution principles generated by the program

3 Conclusions and Further Work

The long-term aim of the research project outlined in this paper is to support the essential generate-evaluate-modify design cycle, by allowing designers to generate device functionality, solution principle alternatives and their physical embodiments, and to envision their side-

effects, so as to modify them in any of these stages. So far, we have developed a representation based on a message/medium concept to represent sensor design functions, devices and principles, have identified a set of elementary devices by analysing a range of existing sensors, and have developed a program for exhaustive automated compositional synthesis of these devices into solution principles for sensor design problems. The performance of the program has been tested by comparing the principles it synthesised with those that a group of designers generated for a common design problem for a real micro-sensor design project. The comparison shows that the software suggests principles which designers considered as well as new viable principles which they did not, demonstrating its potential for expanding designers' creative thinking for solutions. However, the solutions do not presently involve computational devices, feedbacks, or discrete devices. Further work will try to expand the scope of the software to tackle some of these issues as well as to meet the other objectives mentioned in the introduction so as to support the complete generate-evaluate-modify cycle.

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