Performance-Driven Microfabrication-Oriented Methodology for MEMS Conceptual Design with Application in Microfluidic Device Design

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***Abstract*—Performance and manufacturability are two important issues that must be taken into account during MEMS design. Existing MEMS design models or systems follow a process-driven design paradigm, that is, design starts from the specification of process sequence or the customization of foundry-ready process template. There has been essentially no methodology or model that supports generic, high-level design synthesis for MEMS conceptual design. As a result, there lacks a basis for specifying the initial process sequences. To address this problem, this paper proposes a performance-driven, microfabrication-oriented methodology for MEMS conceptual design. A unified behaviour representation method is proposed which incorporates information of both physical interactions and chemical/biological/other reactions. Based on this method, a behavioural process based design synthesis model is proposed, which exploits multidisciplinary phenomena for design solutions, including both the structural components and their configuration for the MEMS device, as well as the necessary substances for the chemical/biological/other reactions. The model supports both forward and backward synthetic search for suitable phenomena. To ensure manufacturability, a strategy of using microfabrication-oriented phenomena as design knowledge is proposed, where the phenomena are developed from existing MEMS devices that have associated MEMS-specific microfabrication processes or foundry-ready process templates. To test the applicability of the proposed methodology, the paper also studies microfluidic device design and uses a micro-pump design for the case study.**

***Index Terms*— MEMS, Behaviour, conceptual design, microfluidic device.**

I. Introduction

MEMS development has been growing steadily over the past several decades. Despite the growth, the prolonged time of product development cycle is still a major problem. As was pointed out by Hsu [1], it used to take an average of 5 years to develop a new microsystem product and another 5 years to have the product to reach the marketplace. Silva [2] also stated that for MEMS product development, typical concept to product development and release cycle has been ~15 years. There could be many reasons for this observation, one of which is the lack of a comprehensive and effective MEMS design model or methodology that cover conceptual design through detail design of MEMS product development process. The lack of standard or formalised process and lack of adequate design tools has led to the “build and test” approach to MEMS product development [2].

To tackle this problem, many researches have been carried out, from both academic and industrial efforts. Various strategies and methodologies have been proposed to support MEMS design. CAD tools have also been developed in implementing these strategies and methodologies [3]. A number of commercial software systems are also available, such as IntelliSense, CoventorWare and MEMSCAP. However, in general, all these existing models or systems follow a process-driven design paradigm, that is, the design starts from the specification of process sequence or the customization of foundry-ready process template. 3D geometry of the MEMS device is then derived from this process sequence and the mask layout, if any. Material, device and process-related properties are then specified for physical/behavioural analysis and simulation; followed by the abstraction of macro-models (or lumped-element network models) for overall system verification and evaluation. This design strategy leaves behind a neglected area of design support, that is, there has been essentially no methodology or model that supports generic, high-level design synthesis for MEMS conceptual design. Obviously, designers must have a design concept first (even though it may only reside in

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their brains from brain-storming), before they can specify process sequences by using their process-related design expertise.

To bridge this gap, this paper proposes a performance-driven, microfabrication-oriented design methodology for MEMS conceptual design. In the next sections, we first conduct a brief literature review of the relevant conceptual design methodologies for general product design, as well as those for MEMS design. By identifying MEMS conceptual design characteristics distinct from those of the general product designs, we then propose a number of strategies and methods specific for MEMS conceptual design. A software prototype implementing these strategies and methods will be presented subsequently. To demonstrate the usefulness and applicability of the proposed methodology, we will also study microfluidic device design and use a micro-pump design as our case study.

II. LITERATURE REVIEW

Conceptual design may be recognised as a transformation process, whereby the design specification of functional and other requirements is transformed into design description satisfying these requirements. It comprises three phases: formulation, synthesis and evaluation [4]. Of these three phases, design synthesis is the most critical one because it involves identification of design solutions. In industry, a number of methods are employed in search for design ideas, such as brain-storming, Method 635, Delphi method [5]; trigger-work, checklist, morphological analysis, attribute-seeking [6]; Unified Structured Inventive Thinking (USIT), and analogies [2].

From the research community, many design methods, models and theories have been proposed, which attempt to formalise the design synthesis process. One representative and well-recognised design theory is the Systematic Design Theory [5], which is originated from German design researches and practices. Briefly, it adopts an input-output relation analysis and synthesis approach for finding design solutions, that is, first identifying all the inputs and outputs of the system to be designed; then the so-called generally valid functions [5], each providing its own inputs and outputs, can be connected to form the inputs and outputs of the desired system. These generally valid functions are derived by analysis of the characteristics of existing systems *a priori*.

Over the past ten to twenty years, the focus of design research has shifted towards the design models and methodologies that not only formalise design synthesis process but also allow IT or computer support. Some of the representative recent design synthesis models (excluding those analogy-based models, adaptive models, case-based models, *etc.*) include the functional synthesis model by Chakrabarti and Bligh [7], the FBS (Function-Behaviour-State) model by Tomiyama et al. [8] and Umeda et al. [9], and the FEBS (Function-Environment-Behaviour-Structure) model by Deng et al. [10]. All these design models use various kinds of building blocks to synthesize design solutions. These building blocks all involve design characteristics of one kind or another. Designers can interactively construct the design from the building blocks by applying their own design expertises. To make full use of IT support, automatic synthesis may be implemented by either combination of the building blocks guided by rules or constraints, or by automatically identifying individual building blocks through certain synthetic search or reasoning mechanisms. The former option may lead to combinatorial explosion, if the employed rules or constraints are insufficient or inadequate. In this regard, the latter option is more efficient.

For MEMS conceptual design, there are a few existing design synthesis models. These models, however, are very restrictive in supporting MEMS conceptual design due to the fact that they are only applicable to specific or specific types of designs, where building blocks for design synthesis have to be pre-specified by the designers. Antonsson [11] has given an overview of design synthesis research for MEMS design. For example, Mukherjee and Fedder [12] have presented a structured design method for MEMS design synthesis. Their work focused on optimal parametric design of the pre-defined design structure, in order to best meet the performance requirements. There is no support for the conceptualization of the initial design structures. Other representative examples not listed in [11] include the automated design synthesis method for MEMS design by Zhou et al. [13] and the design automation model for MEMS design synthesis proposed by Gibson et al. [14]. The former model synthesizes design solutions from some parameterised basic MEMS building blocks by using a GA based evolutionary algorithm. The synthesis algorithms only determine the best topologies and parameters for the selected configuration of building blocks, thus not covering conceptual design.

The latter model uses MEMS device behaviours as building blocks (design primitives), which are at higher level of abstraction than otherwise if structural components are used as building blocks. This is quite similar to the aforementioned design models for general product design. One big limitation of this model is that there lacks a generic and formal behaviour representation method, thus limits the model to be applicable to only specific MEMS designs or specific types of MEMS designs.

As can be seen, there has been essentially no existing design methodology or model that supports generic, high-level design synthesis for MEMS conceptual design. Unlike general product conceptual design, there is no FBS or FEBS like model that specifically support MEMS conceptual design. To address this problem, we attempt to adapt FEBS model to develop a model specifically for MEMS conceptual design synthesis. There are two reasons for selecting FEBS model as our starting point. Firstly, FEBS model represents behaviour by physical interactions.

This behaviour representation is more generic than that of other design models, such as the input-output flow of energy, material and signal, and the state transition. This is because, using input-output flow of energy, material and signal to characterise behaviour may face difficulty if the behaviour does not involve input-output flow that is to the interest of the designers (*e.g.* the behaviour of a fixture). On the other hand, state transition approach is not effective when there is no state change involved (*e.g.* static behaviour). Secondly, FEBS model uses behavioural reasoning strategy to reason out the required individual behaviours during design synthesis (synthesis of system behaviour), rather than by combination of pre-defined individual behaviours, thus is more efficient.

III. MEMS CONCEPTUAL DESIGN METHODOLOGY

A. *Characteristics of MEMS conceptual design*

MEMS devices are primarily used as sensors or actuators. MEMS sensors measure pressure, strain, acceleration, angular-rate-of-change, temperature, fluid flow, fluid viscosity, and more. MEMS actuator systems control power switches and relays; RF- and microwave controlled devices; fluidic valves and pumps; mirrors; fibre aligners and controllable filters; and inductors and capacitors [3]. Hence, MEMS conceptual design is focused on systems design of micro-sensors and micro-actuators.

Adopting the FEBS design methodology, the required individual behaviours for the desired sensor or actuator system should be reasoned out by exploring the relevant physical phenomena and their associated physical principles/laws. However, MEMS system behaviour may involve chemical/biological/other reactions, in addition to physical interactions. Hence, MEMS design involves multidisciplinary science and engineering principles, not just physical phenomena and physical principles. For example, the design of microfluidic MEMS devices used in bio-medical research may require knowledge in a variety of fields such as fluidics, molecular biology, chemistry, physical chemistry, and so on. As such, we need to adapt the representation of behaviour and phenomenon, as well as their application in the design synthesis process.

Another characteristic of MEMS design is that many MEMS design problems not only require development of the physical structure of the design itself; they may also involve selection of a suitable substance (chemical/biological/other) to enable the accomplishment of the desired function. For example, in microfluidic system design, we not only need to design the micro-channel layout structure, the micro-pumps, the micro-valves, *etc.*; but also to select suitable fluids used for the system. Besides, the use of different fluids may affect the physical structure of the microfluidic system.

B. *Unified behaviour representation*

To take into account the chemical/biological/other reactions as a constituent part of MEMS system behaviour, we propose a *unified behaviour representation*, which characterises behaviour by both physical interactions and chemical/biological/other reactions. It incorporates the following aspects of information (indicated by the corresponding variables):

- Inputs: input actions: IA1, IA2, …,
  input substances: IS1, IS2, …,
- Outputs: output actions: OA1, OA2, …,
  output substances: OS1, OS2, …,

where the inputs and outputs can be both the intended and unintended. The structural components that are involved in the behaviour, which may be part or whole of the desired MEMS device, are called behaviour actor. Behaviour actor can be represented as:

- Behaviour actor: structural components: C1, C2, …,
  configuration of the components.

To accomplish a behaviour, the behaviour actor must have working environment, which provides inputs to the behaviour actor and accepts outputs from the behaviour actor. The environment of a behaviour can be part of the MEMS device other than the behaviour actor, or the working environment of the MEMS device itself.

The inputs, outputs and structural components used in the above behaviour representation may be characterised by a number of attributes. The attributes for input/output actions can be the physical parameters describing the actions. For example, if an input action is “IA1 = to supply electricity”, or simply “IA1 = electricity”, then two useful attributes for IA1 may be “potential of IA1” and “current of IA1”. The attributes for input/output substances and those for the behaviour actor can be anything describing the substances or the structural components that are to the interest of the designers. By “to the interest of the designers”, we mean that the attributes either contribute to the accomplishment of the behaviour or affect the behaviour. For example, some useful attributes of a substance may include its material, chemical composition, *etc.* Some useful attributes of a structural component may include its material, shape, size, *etc.* Figure 1 illustrates this behaviour representation method.

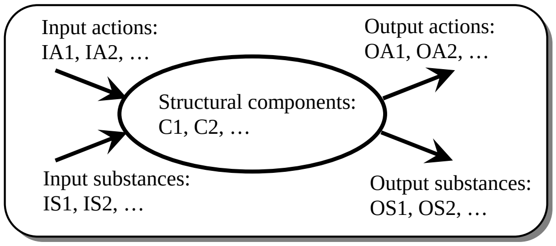


Fig. 1. Unified behaviour representation

The system-level MEMS device behaviour should be implemented by a number of low-level (or various levels, depending on the complexity of the design problem) individual behaviours accomplished by the device’s constituent components and those substances used to perform chemical/biological/other reactions, if any. These individual behaviours collectively form a behavioural process. Identification of these individual behaviours will lead to the identification of the relevant structural components and the required substances, as well as the configuration of the components, thus the design concepts. The behavioural process can be represented by a digraph of individual behaviours, formed by connecting the outputs of a preceding behaviour to the inputs of a succeeding behaviour.

Different from the causal behavioural process (CBP) used in the FEBS design model, the input-output pairs linking two behaviours in the proposed behavioural process may be a substance used for chemical/biological/other reactions, not just input/output actions. These input-output pairs are referred to as *interior* inputs/outputs. They are produced from the preceding behaviours and used by the succeeding behaviours. The *exterior* inputs/outputs refer to the physical interactions taking place between the structural components of the MEMS device and the device's working environment; or they can be the substances either added from the environment or produced to the environment. The exterior inputs/outputs are in fact system-level inputs/outputs of the MEMS device.

C. Behavioural process based MEMS design synthesis

Each individual behaviour within a behavioural process corresponds to a phenomenon, including physical/chemical/ biological/other phenomenon (thus it is a multidisciplinary phenomenon), which is governed by one or more working principles or laws. A phenomenon may be regarded as a generalisation of a distinctive behaviour or behavioural process, hence it incorporates the same information as a behaviour. The only difference between a phenomenon and a behaviour is that a phenomenon corresponds to a generalised chunk of knowledge, not specific to any particular design. Designers can exploit all possible phenomena based on their own knowledge or based on formalised knowledge libraries stored *a priori*, so as to identify the individual behaviours for the development of the behavioural process.

Based on the unified behaviour representation presented in the above section, we propose a *behavioural process based design synthesis* method for MEMS conceptual design. This is a bidirectional synthetic search process. It starts from either the available exterior inputs (by using forward synthetic search), or the desired exterior outputs (by using backward synthetic search). It develops the behavioural process by finding a suitable phenomenon for each individual behaviour. After an individual behaviour is identified, its own inputs/outputs will start another synthetic search. The process goes on until

- for the forward synthetic search, all the required exterior outputs have been produced by the identified individual behaviours;
- for the backward synthetic search, all the required inputs of the identified individual behaviours can be provided by either the working environment, or the other individual behaviours.

Forward synthetic search starts from a known input/output, which can be either an exterior input or an interior output from an existing individual behaviour. It aims at determining whether a new individual behaviour (a succeeding behaviour) or the working environment can make use of this known input/output. Figure 2 illustrates two situations, where "E" stands for the working environment, "B_i" and "B_j" stand for the two individual behaviours. When the known input/output is an interior output from an existing behaviour, say B_i (see situation No.2), the working environment should be searched first (*i.e.* take Option 1 first). If this interior output can be used by the working environment, which means it is actually an exterior output, the search process should be stopped for this behaviour (B_i). Only after the working environment has been searched, should the designers or the automated program searches the phenomena so as to develop a succeeding individual behaviour. When searching for a suitable phenomenon, all the inputs of the available candidate phenomena should be looked up and compared with the known inputs/outputs.

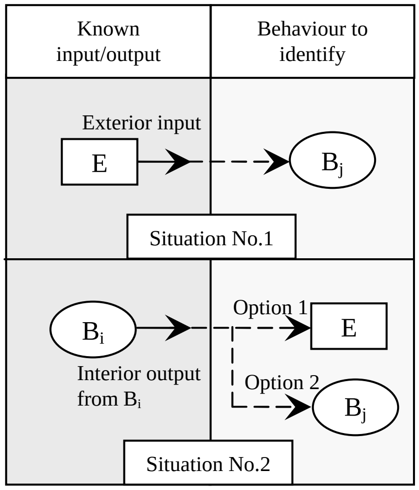


Fig. 2. Forward synthetic search for a behaviour

Backward synthetic search starts from an exterior output, or a required interior input to an existing individual behaviour. It aims at determining whether a new individual behaviour (a preceding behaviour) or the working environment can provide this required input/output. Figure 3 illustrates two situations for backward synthetic search. Similar to forward synthetic search, when the input/output used to initiate the search is an interior input to an existing behaviour, say B_j (see situation No.2), the working environment should be searched first (*i.e.* take Option 1 first). If this interior input can be provided by the working environment, which means it is actually an exterior input, the search process should be stopped for this behaviour (B_j).

Also, when searching for a suitable phenomenon, all the outputs of the available candidate phenomena should be looked up and compared with the known inputs/outputs.

The design synthesis may be performed interactively or automatically, depending on the availability of phenomena design knowledge. By default, automatic synthetic search is conducted first for the specification of each behaviour node. If there is more than one matched phenomenon, designers will be prompted to choose one or more (which will end up with multiple design concepts) from these phenomena. If no phenomenon is found, it is imperative for the designers to specify the behaviour by using their own design knowledge and expertise. Such a behaviour may then be stored as a phenomenon for future use.

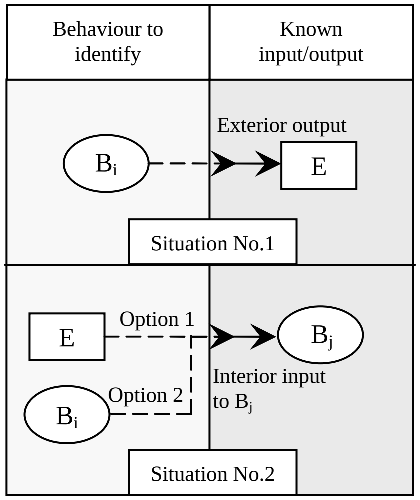


Fig. 3. Backward synthetic search for a behaviour

After design synthesis, all the behaviour actors from the developed behavioural process can be used to construct the physical structure of the MEMS device. The physical structure, together with the identified substances for chemical/biological/other reactions, are then regarded as the conceptual design outcome.

D. *Microfabrication-oriented multidisciplinary phenomena as design knowledge*

The proposed behavioural process based design synthesis method requires the available multidisciplinary phenomena as background design knowledge. This design knowledge may exist as designers' expertise (experience), or it may be formalised as design knowledge base so that the computer program can perform automatic design synthesis. Knowledge acquisition becomes an important part of work in materialisation of the proposed design synthesis method. Various sources and methods for knowledge acquisition may be employed in this regard (a further discussion of this is beyond the scope of this article).

Since multidisciplinary phenomena are the knowledge source for finding design solutions, the manufacturability of the designed MEMS device rely largely on the manufacturability of the behaviour actors of these phenomena. As such, we propose to acquire microfabrication-oriented phenomena as design knowledge. These phenomena should be generalised from those found in the existing MEMS devices. The components of these MEMS devices should have associated MEMS-specific microfabrication processes or foundry-ready process templates.

It should be noted, however, that it is not possible to ensure absolute manufacturability during conceptual design stage, because there lacks detailed information of the design concepts, such as the exact shape, size, even material of the device being designed. By using microfabrication-oriented phenomena, we can make the design concepts as much manufacturable as possible at the early design stage.

IV. APPLICATION IN MICROFLUIDIC DEVICE DESIGN

A. *Microfluidic device design*

Microfluidics refers to a set of technologies that control the flow and chemical/biological/other reactions of minute amounts of liquids or gases – typically measured in nano and picolitres – in a miniaturized system [15]. Great success has been achieved in applications such as ink-jet printers and lab-on-a-chip assays. There are also a variety of potential or new areas of application, such as pharmaceuticals, biotechnology, life sciences, defence and public health.

The development of microfluidic devices involves the fulfilment of system behaviour of "fluid movement and control" in order to achieve one or more required functions. Existing microfluidic devices generally use electrokinetic and pressure methods in delivering such system behaviour. The necessary components used in a microfluidic system include micro-pumps, valves, channels, sensors, *etc.*, where the micro-channel layouts are designed to achieve fluid mixing, separation, delay, reaction, and so on. In the next section, we will apply the proposed MEMS conceptual design methods in developing a micro-pump design.

B. *Design case: a micro-pump design*

Micro-pump design requires an actuation mechanism such as Piezoelectric [16] or magnetic actuator. In this paper, we use magnetically actuated micro-pump design as our design case study. For pedagogical purpose, we first show a typical structure in Figure 4, which consists of a chamber with inlet and outlet valves, a membrane, a permanent magnet, an electric magnet, *etc.* In the following, we will elaborate on how this physical structure can be developed.

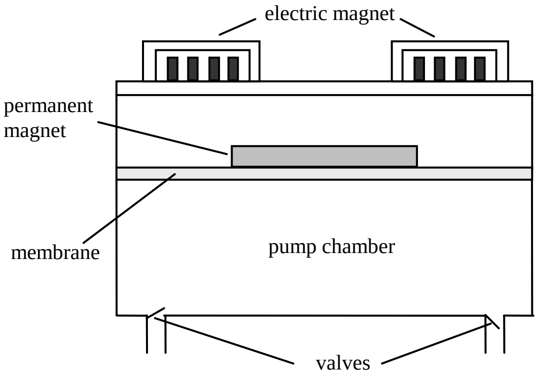


Fig. 4. Illustration of a filament coil

Obviously, the pump must be able to get the working liquid from its source into the pump chamber first, and then to get the liquid out of the chamber into the intended destination. Hence, two behaviour nodes can be created first, one for getting in the liquid, the other for getting out the liquid. Let's develop the first behaviour (denoted as B1) first. There are two required inputs for B1, and also one output action from B1:

- B1IS1 = working liquid (an input substance);
- B1IA1 = to provide action to get in the working liquid (an input action);
- B1OA1 = to get in the working liquid (an output action).

The first input B1IS1 can be easily provided by the working environment, hence an EI node (denoted as EI1) is created and connected with B1. B1OA1 is used as the exterior output, thus an EO node (denoted as EO1) is created and also connected with B1:

- EI1IS1 = working liquid;
- EO1OA1 = to get in the working liquid.

Also, from B1's behaviour actor, the following structural components are identified:

- B1C1 = pump chamber;
- B1C2 = inlet valve.

To provide the required input action for B1IA1, the proposed backward synthetic search method can be applied. Assume that one physical phenomenon is identified, which states that by reducing the pressure inside the chamber, the action to get in the working liquid can be provided. Denoting this behaviour as B2, its required input action and its output action are:

- B2IA1 = to reduce the pressure inside the chamber;
- B2OA1 = to provide action to get in the working liquid.

Further on, to provide B2IA1, another behaviour is required, say B3. By applying backward synthetic search again, it is assumed that a phenomenon is identified: the pressure inside the chamber can be reduced by push outward one or more chamber walls so as to increase the chamber capacity. As such,

- B3IA1 = to pull outward membrane wall of the chamber;
- B3OA1 = to reduce the pressure inside the chamber;
- B3C1 = membrane wall of the chamber.

Further, a yet another behaviour, say B4, is identified, which can provide the required B3IA1. A magnetic phenomenon is found for B4: By attraction between two magnets, the pull action to the membrane wall can be provided:

- B4OA1 = to pull outward the membrane wall of the chamber;
- B4C1 = magnet;
- B4C2 = magnet.

Obviously, one magnet must be fixed with the membrane wall and the two magnets must be positioned so that the action of attraction between the two can be incurred. Since B4 does not require any input, the development process for the behaviour of "getting in the working liquid" can be stopped now.

Following a similar procedure, a behavioural process for the other behaviour, *i.e.* the behaviour of "getting the working liquid out of the chamber", can also be developed. The only differences between this behavioural process and the one already developed are that, the action to the membrane wall of the chamber for this behavioural process should be a "push inward" action, and the valve used should be an outlet valve.

For functional integration, we can try to achieve two behavioural processes by a same set of structural components; or if not possible, by as many same structural components as possible. This is achievable by employing a slightly different phenomenon for the behaviour B4: by using an electric magnet and a permanent magnet (the permanent magnet is fixed with the membrane wall), and alternating the electricity on the coils of the electric magnet, both push and pull action can be provided. As such, we modify B4 as follows:

- B4IA1 = to provide alternating electricity to the electric magnet ;
- B4OA1 = to pull outward or push inward the membrane wall of the chamber;
- B4C1 = permanent magnet;
- B4C2 = electric magnet.

Here B4IA1 can be provided by another exterior input, say EI2:

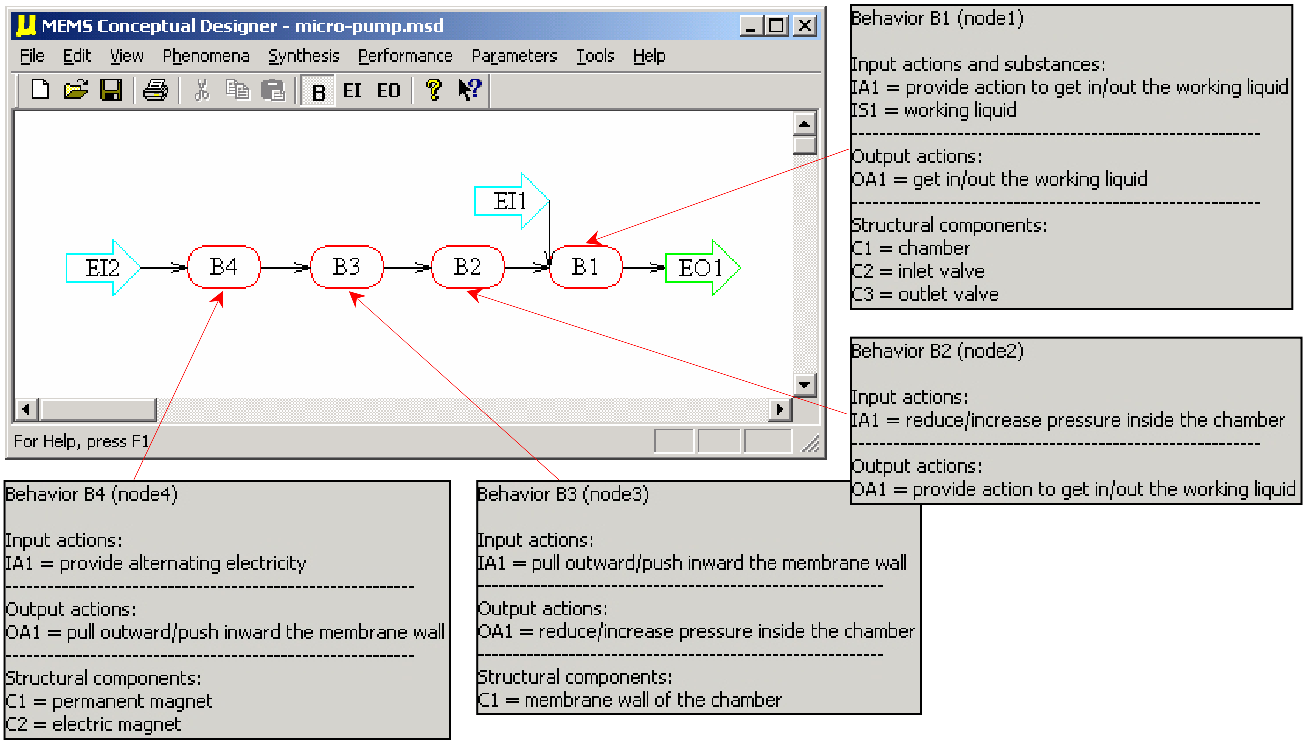
- EI2IA1 = to provide alternating electricity.

Consequently, the specified information for the other behaviours (B1-B3) and EI/EO nodes should be modified accordingly to reflect the two situations represented in a same behavioural process: getting in the working liquid through an inlet valve, and getting the working liquid out through an outlet valve. Figure 5 shows the developed behavioural process, as well as the information of each individual behaviour.

With this behavioural process, the structural components of the micro-pump are known, including B1C1 (chamber), B1C2 (inlet valve), B1C3 (outlet valve), B3C1 (membrane wall of the chamber), B4C1 (permanent magnet) and B4C2 (electric magnet). Their configuration may be determined according to the connection information between their corresponding behaviours as well as that within each of the behaviour actors, *e.g.* B4C1 should be fixed with B3C1. The manufacturability of this design concept is determined by the manufacturability of all the identified components, which are assumed to be without problem at this design stage, because their associated phenomena are all microfabrication-oriented ones. This demonstrates that the desired physical structure achieving the required function of a micro-pump, such as the one shown in Figure 4, can be developed by using the proposed conceptual design synthesis methodology.

V. CONCLUSIONS

The purpose of this paper is to study a generic, high-level design synthesis model for MEMS conceptual design. Based on the existing design models for general (macro-level) product conceptual design, and a study of the characteristics of MEMS conceptual design, we have proposed a number of strategies and methods specific for MEMS conceptual design, *e.g.* a unified behaviour representation method to represent both physical interactions and chemical/biological/ other reactions; a behavioural process based design synthesis model that supports both forward and backward synthetic search; a strategy of using microfabrication-oriented multidisciplinary phenomena as design knowledge to ensure manufacturability at conceptual design stage; *etc.* All these strategies and methods form a MEMS conceptual design synthesis framework, which bridged the gap between the initial design specification and the process-driven design mechanism carried out at the downstream design process. Our continual work will be integrating the proposed conceptual design framework with the existing downstream design activities, so as to achieve seamless transformation between MEMS conceptual design and detail design, and between MEMS design and microfabrication.



Behavior B1 (node1)

Input actions and substances:
IA1 = provide action to get in/out the working liquid
IS1 = working liquid

Output actions:
OA1 = get in/out the working liquid

Structural components:
C1 = chamber
C2 = inlet valve
C3 = outlet valve

Behavior B2 (node2)

Input actions:
IA1 = reduce/increase pressure inside the chamber

Output actions:
OA1 = provide action to get in/out the working liquid

Behavior B4 (node4)

Input actions:
IA1 = provide alternating electricity

Output actions:
OA1 = pull outward/push inward the membrane wall

Structural components:
C1 = permanent magnet
C2 = electric magnet

Behavior B3 (node3)

Input actions:
IA1 = pull outward/push inward the membrane wall

Output actions:
OA1 = reduce/increase pressure inside the chamber

Structural components:
C1 = membrane wall of the chamber

Fig. 5. The behavioural process of the developed micro-pump design

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