MODELING FOR EFFECTIVE COMPUTER SUPPORT TO MEMS PRODUCT DEVELOPMENT

A Thesis

Submitted to the College of Graduate Studies and Research

in Partial Fulfillment of the Requirements

for the Degree of

Master of Science

in the

Department of Mechanical Engineering

University of Saskatchewan

Saskatoon, Saskatchewan

Canada

By

NIRAJ SINHA

PERMISSION TO USE

In presenting this thesis in partial fulfilment of the requirements for a Master of Science degree from the University of Saskatchewan, the author agrees that the Libraries of this University may make it freely available for inspection. The author further agrees that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised the thesis work or, in their absence, by the Head of the Department or the Dean of the College in which the thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without the author's written permission. It is also understood that due recognition shall be given to the author and to the University of Saskatchewan in any scholarly use which may be made of any material in this thesis.

Requests for permission to copy or to make other use of material in this thesis in whole or part should be addressed to:

Head of the Department of Mechanical Engineering
University of Saskatchewan
Saskatoon, Saskatchewan S7N 5A9 CANADA

ABSTRACT

Microelectromechanical systems (MEMS) are miniaturized devices with high functionality. In recent years, MEMS products have become increasingly dominant in every aspect of the commercial market place. As the MEMS technology is in its infant stage and has several unique features compared to macro-scale products, it is faced with several challenges. One of them is that design and fabrication knowledge is very intrigue and thus very difficult to be accessible. An effective computer support to the MEMS product development is thus very important. This thesis study undertakes a thorough investigation into the MEMS product development process and its computer support. Specifically, the study examines the state-of-the-art in computer aided design systems in light of the support of product functionality. It is shown that MEMS product development involves high degree of uncertainty, which calls for an unconventional computer support. At this point, this study proposes an approach to construct a knowledge base in a fairly flexible and real-time manner. This approach is based on the extended function-behavior-structure framework and the template technique proposed in this thesis. The other finding is that the MEMS product development resembles the one-of-a-kind product (OKP) development. Therefore software tools for the OKP product development process can be applied to the MEMS product development process. These tools are examined, and further extensions upon them are proposed. Throughout the thesis, a microdispensing system is used as an example for illustration of concepts described in this thesis.

ACKNOWLEDGEMENTS

Upon the completion of this thesis, I would like to express my sincere gratitude and appreciation to my supervisor Professor Chris W. J. Zhang for his invaluable guidance, constructive discussion, encouragement, and inspiration, without which this work would not have been possible.

My appreciation is extended to the members of the Advisory Committee: Professor R. T. Burton, Professor I. Ogoucha, and Prof. K. Schneider (the external examiner) for their scholarly suggestions, advices and examination in the whole process. I am specially thankful to Prof. P.B. Hertz for his continuous encouragement and support throughout my stay at U of S.

I am greatly indebted to my parents Dr. A. K. Sinha and Mrs. C. Sinha, my siblings Mr. Shashi, Mrs. Pratima, Mrs. Purnima, and Mr. Ashutosh for their continued moral support and love. Their constant encouragement and support in making this work a reality is gratefully acknowledged.

Finally, I thank all my friends in Saskatoon for their useful advice and support throughout this research.

This research was made possible by the financial support from the National Sciences and Engineering Council (NSERC) of Canada.

Dedicated to

My Parents

Dr. A.K. Sinha and Mrs. C. Sinha

For their continuous love and unwavering support!!!

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

ACRONYMS

CAD	Computer Aided Design
CE	Concurrent Engineering
DKT	Domain Knowledge Transformation
FBS	Function Beahviour and Structure
FEBPSS	Function Effect Behaviour Principle State and Structure
FFB	Form Function and Behaviour
FMECA	Failure Modes, Effects and Criticality Analysis
GKB-MEMS	General Knowledge Base for MEMS
ID	Identification
IPMAS	Integrated Preventive Maintenance System
KBS	Knowledge Based System
LOC	Lab-on-a-Chip
MEMS	Microelectormechanical Systems
NSERC	Natural Science and Engineering Research Council
OKP	One-of-a-Kind Production
PAN	Phosphoric, Acetic, Nitric Acids
PM FMECA	Preventive Maintenance Failure Modes, Effects and Criticality Analysis

Chapter 1

Introduction

1.1 Motivation

Microelectromechanical systems (MEMS) refer to devices that have a characteristic length of less than 1 mm but more than 1 μm, that combine electrical or electronics (or both) and mechanical components, and that have moving parts of some kind. Nowadays, the MEMS concept has grown to encompass many other types of small things, including thermal, magnetic, fluidic, and optical devices and systems, with or without moving parts.

The benefits of having smaller components and hence a device or machine with enhanced capabilities and functionalities are obvious from engineering perspectives:

- Smaller systems tend to move more quickly than larger systems because of lower inertia of the mass;
- The minute sizes of small devices encounter fewer problems in thermal distortion and vibration;
- Smaller systems with lower masses have much higher natural frequencies than those expected from most machines and devices in operation.

The most obvious characteristic of MEMS is that they are small. Yet, the most important characteristic of MEMS is that they can be made in batches.

In recent years, enormous progress has been made in developing new fabrication techniques for making small things. MEMS product development has become an active area of research. There is no doubt that MEMS products have many unique features compared to macro products; yet, there is a lack of research on understanding the MEMS product development process and its computer support. This thesis study was motivated by a need to conduct a thorough investigation into the MEMS product development process and its computer support.

1.2 Problem Analysis

At the beginning, various microfabrication techniques were reviewed, and various computer aided approaches for macro-scale systems were reviewed and analyzed for their suitability for MEMS products. Like macro products, there are two basic problems in any computer aided design system for MEMS products: (1) design knowledge representation and management, and (2) design process representation and management. This literature analysis has made several observations. First, the contemporary microfabrication techniques were not matured; the performances with these techniques were very sensitive to materials used and to process parameters [Rai-Choudhury, 1997]. Simulation of microfabrication processes was extremely difficult. Second, the availability of a particular microfabrication process to a MEMS product design per se was very poor. This further means that often available microfabrication processes drove the development processes, which increased the uncertainty in MEMS product development. Third, contemporary computer aided design systems/tools apparently focussed on the design of the product structure only. Explicit representation of functions of a product and links between functions and structures were generally lacking. There were some studies attempted to incorporate functions into a computer aided design system; notably the one which may be called function-behaviour-structure (FBS) framework [Gero, 1990; Umeda et al., 1990]. They, however, did not provide method for representation, not even a conceptual representation. Conceptual modeling of function, behaviour, and structure was attempted by Zhang et al. [1994] in the restricted area of mechanism design. Fourth, there was lack of a systematic approach to build or update a knowledge base quickly. The emphasis on ‘quick’ and ‘update’ was considered to be very important to MEMS product development because the rate of technological change in this area was very high. Overall, this preliminary analysis led to the setting of the research objectives (or hypothesis) of this thesis study; see the next section.

1.3 Research Objectives, Scope, and Significance

The following objectives are defined for this thesis study:

> ***Objective 1:*** *To analyze the MEMS product development process and to validate the statement that the contemporary computer aided design methods / tools are not suitable for MEMS product development, which further calls for a general approach to a new computer aided design method/tool for MEMS products.*

The method applied to achieve this objective is to conduct an in-depth literature study to identify unique features associated with MEMS product development process and to generalize features which are supplied by the contemporary computer aided design methods/tools. Comparison of these two categories of features should achieve the objective.

> ***Objective 2:*** *To investigate the methodology for rapidly building or updating a design knowledge base for MEMS product development.*

The method applied to achieve this objective is to apply the so-called framework technology [van der Wolf, 1993]. The framework technology puts emphasis on identification of concepts with which a system can be built. Another idea is to develop a set of templates for representing knowledge at different levels. It is assumed that these templates are modules, and they can be assembled into a concrete knowledge base for a specific design problem. Templates can be considered as an implementation vehicle for concepts identified.

> ***Objective 3:*** *To analyze the computer aided design process management for MEMS products; in particular to identify unique features with the MEMS product development and to evaluate whether and how existing workflow management tools are applicable to effective MEMS product development process.*

To achieve this objective, the contemporary workflow management methods/tools is examined. For relatively earlier work on the computer based workflow management in engineering design should refer to Zhang and van Luttervelt [1995]. More recent comprehensive studies using Petri Net on workflow management should refer to van der Aalst [1998].

Overall, the general methodology for conducting this research is to employ an MEMS product as an example throughout. It is noted that this thesis study is not going to develop any software, though in the mind of the author, this should be a desire from a practical viewpoint. Nevertheless, the result of the thesis work will serve as a foundation for any kind of scenario within which a concrete product, such as software, can be developed.

1.4 A Remark on General Research Methodology

Two types of scientific research approaches can be identified in the methodological literature, namely, the theory-developing or analytic research approach and the design-oriented or applied research approach [van Stekelenborg, 1996]. The differences in these approaches arise from the purpose of the research and the techniques that are used and not from the structure and the methods that are applied. Theory-developing research is descriptive as it describes, explains, and predicts phenomena. Design-oriented research is prescriptive, focusing on the guidelines and procedures actually needed to change phenomena. A validation of the soundness of design-oriented research is done by means of case studies. The research work described in this thesis is of the design-oriented type. This implies that the result of the research is an artefact, which is imperative, normative, and prescriptive.

1.5 Organization of the Thesis

The remainder of the thesis will be organized as follows. Chapter 2 will provide a literature review to give further justification of the significance of the proposed work, particularly with respect to the research objectives set in Chapter 1. Chapter 3 provides an example of a fluid dispensing system for MEMS applications with which the complexity involved with the development of MEMS products is elaborated. This elaboration will show a need to extend the existing computing technology to MEMS product development in the two areas: the management of the MEMS product development process and a general (flexible) knowledge based system. Chapter 4 gives a further analysis and proposes the solution to the MEMS product development process. Chapter 5 proposes a general approach to building a general knowledge based for MEMS product development. Chapter 6 presents a case study to show how the general knowledge base helps to conduct MEMS product development more effectively. Chapter 7 is a conclusion with recommendations for further studies.

Chapter 2

Literature Review

2.1 Introduction

The purpose of this chapter is to provide further justification to the significance of the research setting developed in Chapter 1, in particular those related to research objectives. A critical review of the related work reported in literature will fulfill this purpose. This chapter also provides background knowledge for facilitating subsequent discussions. Section 2.2 will discuss function-behaviour structure model, which is a foundation for developing a knowledge base. This includes a discussion on the characteristics of different schools of modeling and a comparison between them. This is related to the research objective 2. Section 2.3 discusses the general design process and its computer support. This is related to the research objective 3. It is noted that a more comprehensive discussion of computer based design process management is presented in Chapter 4. In Section 2.4, studies on computer aided MEMS design are reviewed, which will give some general impression of computer aided MEMS design in light of the need of a more effective computer aided design with integrated consideration of functions and structures. Section 2.5 contains general concluding remarks.

2.2 Function-Behaviour -Structure Model

2.2.1 Basic Concepts

A ***model*** is the representation of a thing that could be a real world entity, a process, or an event. A process to develop a model is called ***modeling***. In a Function-Behaviour - Structure (FBS) framework, three main perspectives are studied. These are function, behaviour, and structure. Because any thing has these aspects, i.e., structure, behaviour, and function, there are at least three models corresponding to a thing. The purpose of modeling is to explore the structure, behaviour, and function of a thing and the relationships among them. There are different schools of thought for FBS modeling that are discussed in Section 2.2.2.

2.2.2 Different Schools of FBS Modeling Approaches

The words function, behaviour, and structure are referred to and used in various fields, such as design, production, and artificial intelligence. The origin of the concept of function, behaviour, and structure goes back to seventies when Rodenacker [1971] proposed a design methodology as a guideline for novice designers. In his methodology, a designer first determines the entire function of an entity from the given specification. The function is divided into sub-functions, sub-functions into sub-sub-functions, and so on, until the level where physical behaviours perform such sub-functions. Subsequently, the functional structure is copied to the physical structure. Since then many researchers have provided various approaches to function, behaviour, and structure. Function-behaviour-structure (FBS) modeling approaches can be categorized into different schools based on their perception. The following is a brief overview of different schools and their respective modeling approaches.

School 1: *Australian school of modeling*

The propositions for FBS modeling in this school are made mainly by Rosenman and Gero [1998], Gero et al., [1992], and Scott and PakSan [2001a, 2001b]. Rosenman and Gero [1998] put forward following definitions:

Purpose: the reason why an artefact exists or why it is what it is, what it is intended for;
Function: what is performed by an artefact;
Behaviour: the manner in which an artefact acts under specified conditions;
Structure: what constitutes an artefact (or defines its constitution).

If a comparison is made between the purpose and the function, then it is found that a purpose is an intended function. In other words, purpose is a subset of function as an artefact can have many functions. For example, a motor car carries things, exhausts fumes, makes noise, etc. The last two do not fall into the domain of purpose.

According to Scott and PakSan [2001a, 2001b], behaviour acts as a link between function and structure. The incorporation of behaviour breaks the rigid coupling between structure and function.

School 2: *Japanese school of modeling*

This school [Umeda et al., 1990, 1996] defines a function as a "description of behaviour abstracted by human through recognition of the behaviour in order to utilize the behaviour" and behaviour as "sequential state transitions along time." According to them, following are the three roles of function:

- As a modelling language by which designers can compose and develop their requirements.
- It serves in object representations that can connect requirements and objects.
- After the development and deliberation of objects, function is used to assess how well their purpose is satisfied.

FBS modeling is proposed by them to support these three roles of function. They differentiate between the function and behaviour by stating that the behaviour can be directly derived from the state of objects and their environment, but function is also related to the perception of the object by designers in addition to the state of objects and their environment.

School 3: *American school of modeling*

The first definition of function, behaviour, and structure in the United States was proposed by De Kleer [1984]. According to him, structure is 'what the device is,' behaviour is ‘what the device does,’ and function is ‘what the device is for.’ Later, Chang et al. [2000] advocated an integrated form, function, and behaviour (FFB) based modeling framework. According to them, combining form, function, and behaviour can satisfy all necessary criteria for a representation system and a more robust and complete representation system can be realized. Some of their propositions can be summarized as

- Function is never enough for representation;
- Function is a subset of behaviour;
- Form is seldom practical; function and behaviour need to be associated with it for complete representation of a system;
- Representing behaviour is difficult due to the fact that the totality of behaviour is more complex than its parts.

School 4: *European school of modeling*

This school [Zhang, 1994; Zhang et al., 1998] puts forward following definitions:

Function: is the usefulness of the behaviour, perceived by the human user;
Behaviour: is a description of the system in terms of its allowable states, the system’s variables, and how those variables are related;
Structure: is how the behaviour is realized.

While this definition resembles with the one given by De Kleer [1984], a description of these concepts form a computational and data modeling viewpoint, and they were attempted [Zhang, 1994; Zhang et al., 1998] using the mechanism design as an example. One important feature of their approach is that they proposed a “plug-and-play” strategy to allow users to plug their defined functions and behaviours into the knowledge base for a particular design problem. This is because a system can have different types of behaviours of interest to different applications, and one behaviour can be used for different purposes, (i.e., functions). They made the plug-and-play strategy possible because they defined the interfaces among structures, behaviours, and functions.

2.2.3 Remarks on Existing FBS Modeling Approaches

One big concern with all these studies on FBS modeling is that they do not seem to provide a mechanism for representing these concepts with a data structure, except the work performed by Zhang [1994]. This has already hindered an effective computer aided design for applications. In most of the studies on computer aided design, there is seldom a report on data representation of knowledge in a general way. The next section provides more justification on this observation. Furthermore, they have many concerns with different terms. For instance, the concept called purpose in Rosenamn and Gero [1998] is the same as the concept called function in Umeda et al. [1990]. This perhaps further hinders the computer implementation of these theoretical studies.

2.3 Design Process

Design exists because the world around us does not suit us and the goal of designers is to change the world through the creation of artefacts. Design can be defined as a process which generates a model of a designed object in conformity with a set of requirements [Zhang, 1994]. This is done by defining the functions to be achieved (with constraints) and producing descriptions of the artefacts capable of generating these functions. For example, there is a need to dispense fluids in the order of nano-litre. This implies a function. This function can be achieved with the help of a special device or fluid dispenser (description of the artefact).

The goals of design research are better understanding of the design process, development of tools to aid the human designer, and automation of some of the design tasks. The design can be represented in graphical, numerical, or textual way, the aim being the transfer of sufficient information about the designed artefact so that it can be manufactured, fabricated, or constructed.

2.3.1 Knowledge-Based System (KBS) Design Process

The design of a knowledge-based system takes place in following phases [Guida and Tasso, 1994]:

(i) Opportunity analysis: the purpose of the opportunity analysis is to define a strategic, long-term plan for the correct and effective introduction of knowledge-based technology into an organization.

(ii) Plausibility study: the purpose of the plausibility study phase is to evaluate whether the conditions exist to make a potential knowledge-based system project possible, and to help make the first set of basic technical and organizational choices.

(iii) Construction of the demonstrator: the objective of the construction of the demonstrator phase is to develop a running system, namely the demonstrator, which can anticipate a sub-set of the functions of the final KBS.

(iv) Development of the prototype: the development of the prototype is the main endeavour of a KBS project. Its main objective is to find the most suitable solutions for the application considered, and to implement these in a running system.

(v) Implementation, installation, and delivery of the target system: the purpose of this phase is to carry out the various activities needed to implement the target KBS, install it in the operational site, and eventually deliver it to the end-users.

(vi) Maintenance and extension: this phase is of primary importance to ensure a long and effective operational life of the KBS and to exploit all potential benefits of the project.

The technique employed for developing a KBS design is a model generation procedure. It starts with an analysis of the application domain and developing a conceptual model of the involved knowledge and reasoning processes. The conceptual model is then used to incrementally build a model of the KBS, called logical model. This phase is called embodiment design phase. On the basis of the logical model, a detailed design of the KBS is finally produced, which specifies exactly how the software programs and the knowledge bases are implemented by means of the specific development tools chosen. The following section overviews some of the methodologies that have been used by researchers for designing a knowledge-base.

2.3.2 Methodologies for Designing a Knowledge Base

It is observed while reviewing the literature that there is no generic methodology that has been adopted for developing a knowledge-base. Various researchers have used different methodologies for designing knowledge-bases. Zhao et al. [1996] have proposed a domain knowledge transformation (DKT) methodology that can be used at the conceptual design stage of mechanical systems. The DKT model is a two-level process that reveals the insights of the methodology. In the first level, defined as the preconcept level, a list of design specifications is developed through the interaction between an intelligent system and the users or customers. In the second level, defined as the concept level, design solutions are generated using a functional requirements mapping method. Zhang et al. [2001] have proposed a knowledge-based system that supports the synthetic phase of conceptual design. It was developed using an expert system shell called CLIPS.

Duribreux-Cocquebert and Houriez [1996] have presented a methodology based on a multi-model design approach, which views at once a co-operative approach between expert, user, computer engineer, human factor specialist and knowledge engineer for developing acceptable, useful and usable systems. Plant and Tsoumpas [1994] have proposed a rigorous development methodology for knowledge-based systems. The knowledge-based system development methodology is embedded within a two-level life-cycle model. The two levels are termed the macro- and micro-levels. The aim of having two levels is to allow the developer to focus upon each item separately but to understand the factors upon which the factor's development rests and its impact upon the other sub processes.

Marteel et al. [1993] have defined a methodology based on an extension of Failure Modes, Effects and Criticality Analysis (FMECA) that has been called Preventive Maintenance FMECA (PM FMECA). This methodology directly provides the concepts used to build the knowledge base of the maintenance system. This approach is helpful to build and to structure this knowledge base. This rigorous and exhaustive methodology was used to build the generic system integrated preventive maintenance system (IPMAS). Highland and Kornman [1994] have explored a Cleanroom Software Engineering Methodology. The methodology emphasizes the use of stepwise refinement techniques and proofs of correctness to prevent errors early in the development process. This calls for the use of well-defined design language and verification techniques to prove the correctness of the design.

A critical analysis of the methodologies mentioned above reveals that they have certain limitations. As a result, none of them can be used as a generic methodology or framework. For instance, the DKT methodology could be a useful concurrent engineering tool only in the early design stage. Similarly, Zhang et al. [2001] consider only conceptual synthetic design phase, not the analytic design phase. Besides, their system is based on a particular expert system shell. The methodology presented by Highland and Kornman [1994] employs the extensive use of structured English language specifications throughout the process, which makes the approach practical but limits the ability to verify designs using automated tools. Therefore, there is a need of a methodology or framework that can be used as a generic template for designing a knowledge-base.

2.4 Computer Aided MEMS Design

2.4.1 Need of CAD for MEMS

MEMS development is a broad field that combines a large range of technical disciplines. Computer-aided design (CAD) tools are clearly needed to reduce the consumption of development resources, and frequently help provide insight into complex physical processes for the evolution of high aspect ratio micromechanical devices (like pumps, valves, and micromotors) as high performance demands are placed on these devices, especially in precision and accuracy. Whenever they are applicable and useful, software modeling tools rapidly gain acceptance by the design community. CAD tools will permit the rational design of these devices and evaluate the effects of parameters such as temperature, strain, acceleration, etc. [Madou, 1997]. Without CAD tools, fabrication remains in the domain of experts, and evolution of the design process relies on empirical approaches.

In general, the CAD software packages are structured as sketched in Figure 2.1, with the design aids used to create the design, simulation to develop the technology, and verification to check the design [Senturia and Howe, 1990]. The final verification, of course, always happens in the lab. The goal, though, is to avoid wasteful and slow experiments by carrying out less costly computer work in order to get the fabrication right the first time [Maseeh, 1990]. Several CAD systems, which might facilitate the wider acceptance of MEMS, are discussed in the section 2.4.2.

2.4.2 MEMS CAD Software Tools

According to Senturia and Howe [1990], the ideal suites of CAD tools required for MEMS development are:

- Rapid construction and visualization of three-dimensional solid models;
- A database of materials properties;
- Simulation tools for basic physical phenomena (for example, thermal analysis, mechanical and structural analysis, electrostatic analysis, magnetostatic analysis, and fluid analysis);
- Coupled force simulators (for example, thermally induced deformation, electrostatic and magnetostatic actuators, and interaction of fluids with deformable structures);
- Formulation and use of macromodels (for example, lumped mechanical equivalents for complex structures, equivalent electric circuit of a resonant sensor, and feedback representation for coupled-force problems);

- Process simulation or process database (including, lithographic and etch process biases; and process tolerances on thicknesses, lateral dimensions, doping, and resistivity levels);

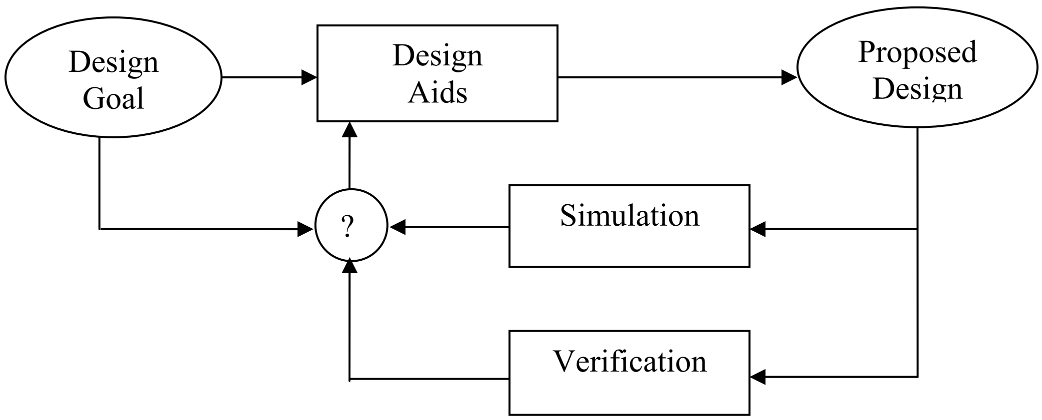


Figure 2.1: Design, simulation, and verification in CAD systems

- Design optimization and sensitivity analysis (for example, variation of device sizing to optimize performance, and analysis of effects of process tolerances);
- Mask layout;
- Design verification (including, construction of a three-dimensional solid model of design using the actual masks and process sequence, checking the design for violation of any design rules imposed by the process, simulation of the expected performance of the design including the construction of macromodels of performance usable in circuit simulators to assess overall system performance);

Some examples of MEMS CAD programs under development and developed so far are IBM's Oyster [Koppleman, 1989], MIT's MEMCAD [Gilbert et al., 1996], the University of Michigan's CAEMEMS [Crary and Zhang, 1990], ETH's SESES [Korvink et al., 1994], and IntelliSense Corp.'s IntelliCAD [Maseeh, 1994]. Oyster facilitates the construction of a three-dimensional polyhedral-based solid mask set and gives a rudimentary process description. MEMCAD is directed at conceptual design and simulation, as well as design verification. CAEMEMS is geared towards design optimization and sensitivity analysis. SESES addresses conceptual design and simulation and design verification. IntelliCAD includes the material database. The material database contains electrical, mechanical, optical, and physical properties of semiconductor thin films collected from the literature.

On a general remark, these tools focus on structure design and indeed have little about design that links functions to structures – a notion called synthesis. Moreover, these tools have not provided design process management. To make the CAD system more flexible, a knowledge base/database system is required that has a very systematic representation with less data and more information and that keeps on updating itself as the new information arrives.

2.5 Conclusion

In the general area of design, the development of intelligent computer support systems for design has been the subject for many years. One of the key technologies is relevant to the modeling of functions and structures. The matured technology is available for modeling functions alone, but neither the function nor the linkage of the function to structure is available. The notable modeling idea is the so-called function-behaviour-structure framework. This framework is not yet unified, which leads to ad-hoc developments of systems for MEMS design. Contemporary CAD tools for MEMS have not considered the process management, which puts a high demand for research on this missing component.

Chapter 3

Complexity in MEMS Product Development

3.1 Introduction

In this chapter, an example of a fluid dispensing system is presented to illustrate complexities involved in the development of MEMS products. This example helps to understand unique features of MEMS product development which will be discussed in Chapter 5. This further helps to justify the need of developing a general knowledge base system for the MEMS product development. This chapter is organized as follows: In Section 3.2, the idea of a fluid dispensing system is given. Section 3.3 discusses the dispensing process in detail. Section 3.4 presents the challenges associated with MEMS product developments using the fluid dispensing system as an example. Section 3.5 is a conclusion.

3.2 A Fluid Dispensing System

There are many applications in medicine, electronics, and chemical industries where the precise control of fluids is important. One of such control methods is fluid dispensing. Fluid dispensing is a process by which fluid materials are delivered from a container in a controlled manner [Dixon et al., 1997]. In the case of drug delivery, fluid materials are delivered into the human body, and in the case of integrated circuits fluid materials are delivered to the board. Figure 3.1 shows four types of fluid dispensing systems in the electronics packaging application [Chen, 2002]. The generic feature with these systems is that there must be a certain pressured force applied on the fluid within a container, and the fluid is forced out of the gate of the container. It should be noted that the types of devices for fluid dispensing, as shown in Figure 3.1, can usually handle the amount of fluids at the level of millilitres (mL).

In some applications, the amount of fluids dispensed is required to be at the levels of microlitre or nanolitre. The macro-size device as the one shown in Figure 3.1 cannot fulfill this requirement. In order to meet the requirement of micro/nano- litre fluid dispensing, the size of the device must be reduced to the realm of hundreds of microns or less. Devices in this realm are now called microelectromechanical systems (MEMS for short). Therefore, MEMS dispensing devices or microdispensing devices are researched in the literature [Tseng, 2002; Nguyen and Wereley, 2002]. Some of the advantages with these microdispensing devices are:

- The ability to work with small objects, which leads to significantly smaller and less expensive biological and chemical analyses;
- The reduced power consumption, which suits microfluidic systems;

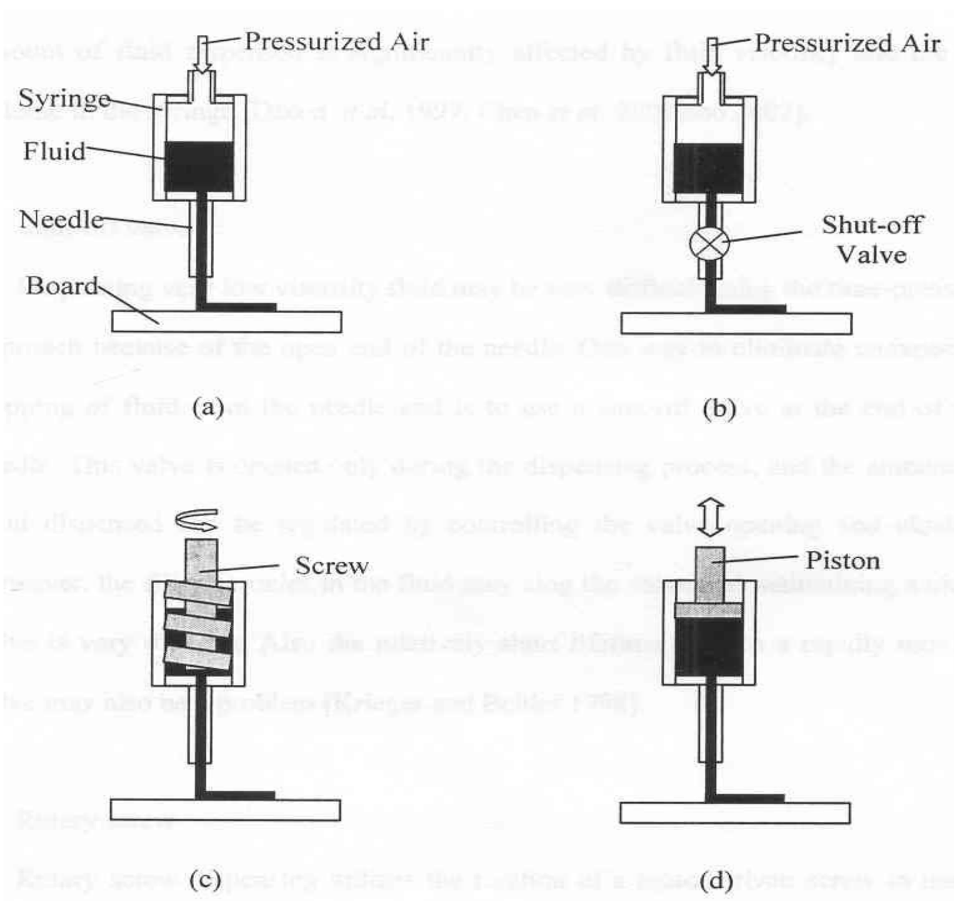


Figure 3.1: Schematic diagrams of fluid dispensing approaches; (a) time-pressure, (b) shut-off valve, (c) rotary screw, and (d) positive displacement [Chen, 2002]

- The facilitation of the integration of microfluidic systems and electronic systems, which is towards a new concept called lab-on-a-chip (LOC); and
- The cost savings due to one step batch production [Tseng, 2002].

3.3 Device Development for Microdispensing Process

In the following, solution concepts/principles for a device which can fulfill the requirements of the micro/nano-litre fluid dispensing, as discussed in Section 3.2, are introduced. Then follows the description of this device.

3.3.1 Solution Concepts and Principles

It is noted that only the space where the fluid is processed needs to be miniaturized, and miniaturization of the entire system is not a requirement in some of the cases. The process of microdispensing proceeds in three phases [Koltay et al., 2001], and they are illustrated in the following:

Phase I: Jet Ejection

To deliver the amount of fluids at the microlitre or nanolitre, the mechanics principle based on the impact is applied. The impact force can create a jerk that gives a high momentum to the fluid such that the fluid gets a high speed. The conceptual structure to achieve such a high impact is illustrated in Figure 3.2.

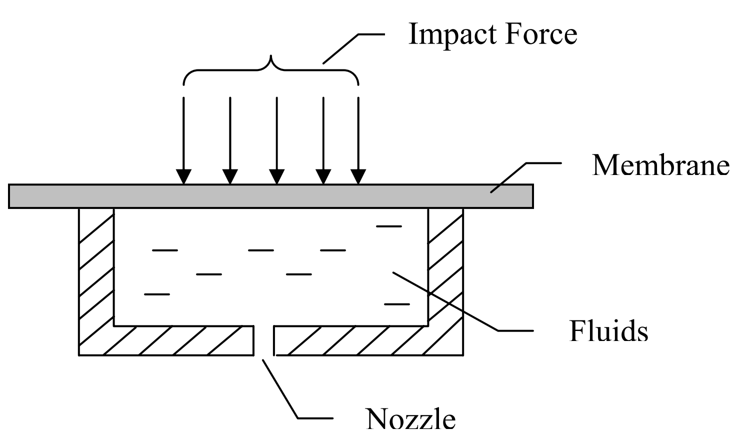


Figure 3.2: The conceptual structure of a dispensing system

When a fast mechanical displacement is applied on the membrane, the mechanical stress so generated produces flexural acoustic waves in the membrane wall. The wave motion of the wall produces a pumping effect to drive the fluid out of the container. The fluid so stimulated flows not only towards the nozzle and ejects but also towards back. This phenomenon was observed experimentally by Koltay et al. [2001]. It is believed that the reason for this backward flow is because of the reaction force generated by the liquid in response to the mechanical stress generated by the membrane. Therefore, a reservoir concept should be in place to retain the backward fluid. While the flow towards the reservoir starts instantaneously, the flow through the nozzle sets on after the pressure inside the microchamber counterbalances the forces induced by the free surface at the nozzle. An accelerated forward movement is needed to generate a jet eventually. Due to the backflow into the reservoir, the ejected volume does not correspond to the whole displaced liquid.

Phase II: Relaxation

After the displacement of the disc has reached its maximum, a short dwell time is needed until the system has reached its new equilibrium. During this time, the fluid flow stops completely and the liquid jet is torn off at the nozzle. During this second phase the disc has to remain static.

Phase III: Refilling

The refilling of the microchamber can be initiated by a slow release of the membrane after a stable meniscus has been formed at the nozzle. The slow release speed is essential for the proper refilling because it has to be ensured that the pressure inside the dosage chamber does not exceed the capillary pressure at the nozzle. Otherwise, the air would be sucked through the nozzle into the dosage chamber and could cause a failure of the whole device. However, if the release of the disc is slow enough, the pressure difference between the microchamber and the ambience never exceeds the critical value, because the flow of liquid from the reservoir continuously compensates the pressure difference. This flow finally leads to the complete refilling of the chamber when the membrane is fully released.

3.3.2 A Device

It is noticed that in the literature, the device that can realize the solution principle mentioned above is also called the droplet generator. Following the discussion of the solution principles, the structures can be determined [Lee et al., 1984]. First, the piezoelectric actuation was applied on to the membrane; see Figure 3.3 [Tseng, 2002]. The working principle of the piezoelectric actuator is shown in Figure 3.4. Application of the voltage produces the mechanical stress in the piezoelectric layer that can be found by Equations (3.1), (3.2), and (3.3).

$$V= f \sigma \quad (3.1)$$

$$\varepsilon= d V \quad (3.2)$$

$$1/f d = E \quad (3.3)$$

where V is the applied electric field (V/m), σ is the generated stress (Pa), f is a constant, ε is the induced strain, d is a piezoelectric coefficient, and E is the young's modulus of the piezoelectric material. The acoustic wave applies force to move the fluid to eject the drops. This completes first phase of the dispensing process as discussed in Section 3.3.1.

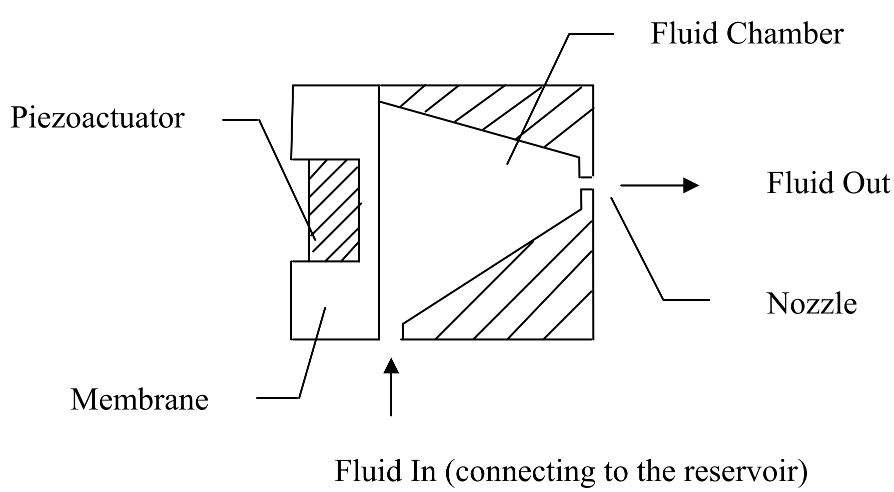


Figure 3.3: Piezoelectric-actuated drop-on-demand dispensing system [Tseng, 2002]

For the physical implementation of the relaxation and the refilling, an elastic membrane and a chamber were designed; see Figure 3.3. Furthermore, a reservoir was designed but is not shown because it is out of the scope of this thesis. It is noted that the complete device can be found in Appendix A.

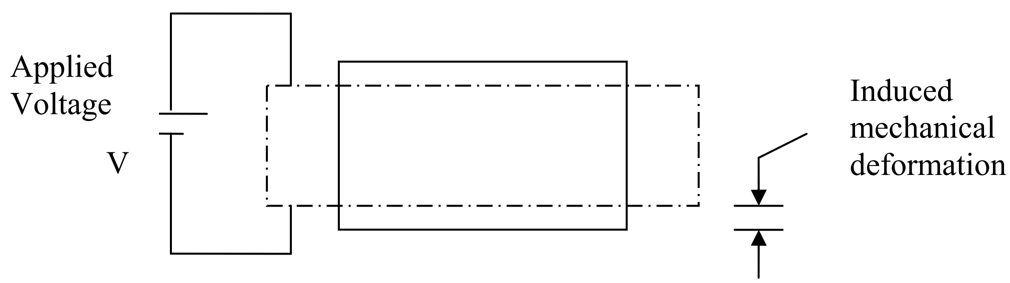


Figure 3.4: Electric voltage induced mechanical deformation

3.3.3 Fabrication of the Device

This device differs from some MEMS devices which are generally 'planar'. The current micro-fabrication techniques can only make in-plane features if the techniques are used alone. For devices which have out-plane features like the one shown in Figure 3.3, the general strategy for building them is to first fabricate the whole system in parts and then join these parts together.

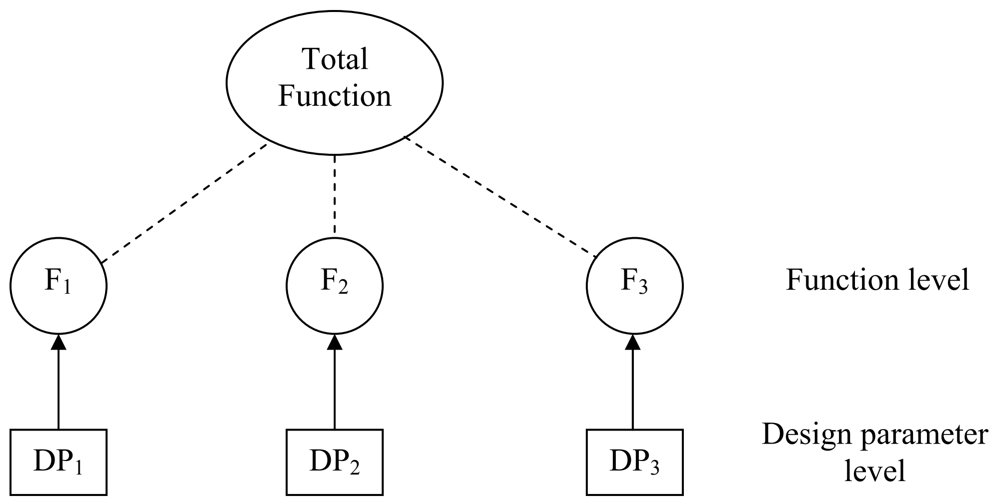
To fabricate the membrane, the first step is the selection of material for wafer. Like microelectronics, silicon is usually preferred as the wafer material. The other materials that can also be used are germanium and gallium arsenide. The general fabrication processes followed are: cleaning of the wafer by RCA cleans; coating of the silicon wafer with the masking layer (silicon nitride or silicon dioxide); applying photoresist by spin casting; etching using potassium hydroxide (KOH) for silicon nitride mask and tetramethyl ammonium hydroxide (TMAH) for silicon dioxide; sputtering of thick titanium and gold layer on the silicon wafer to act as a bonding pad; and finally gluing the actuator and electrical wires on the etched surface using an adhesive [Cao, 2001].

Similarly, the fabrication of the fluid chamber and nozzle requires the following common processes: cleaning of the wafer, coating of the wafer with the masking layer, applying photoresist, and etching (on one side for making the fluid chamber and on the other side for ejection nozzle) [Lee, 2002]. At the end, both parts are joined by a microjoining process to get the structure as shown in Figure 3.3. It is noted that the complete fabrication process can be found in Appendix B.

3.4 Challenges in Developing a MEMS Device

The biggest challenge in developing a MEMS device is posed by the uncertainty involved in the outcome of the fabrication process. This uncertainty can be attributed to (1) very small size of the systems; (2) rapid change in the microfabrication technology, which results in innovation of several new technologies and obsoletion of some existing ones; (3) non-standardized microfabrication processes; and (4) coupling of knowledge from different disciplines of science and engineering. When the overall size of a system goes too small, clearance between different parts, when they are assembled, may become of the same order of sizes as those of parts. Since clearances/tolerances are random variables, system/assembly performance will then be in uncertainty. Change of technologies could lead to the unstable state of the product development and also to the difficulty in system maintenance. Non-standard processes will further hinder the exchange of parts. On one hand, the development of a MEMS product rarely relies on a single company, simply because fabrication techniques are too expensive and are not affordable by one company only. On the other hand, poor interfaces between companies are present. This has implied a paradox associated with MEMS product development. Finally, it is a common sense that knowledge, which is presented as the structure of heterogeneous knowledge components- a way of coupling different units which follow different principles, is more complex. It is noted that this is similar to the viewpoint of axiomatic design theory proposed by Suh [1990]. In his design axiom 1, Suh [1990] stated that a design should render to and maintain functional independencies; see Figure 3.5.

With reference to Figure 3.3, let us consider the design and development of the fluid chamber. The general processes used in developing the part were already outlined in Section 3.3.3. As the size of the part is very small (in the range of hundreds of microns or less), this makes the use of existing macro-scale fabrication processes obsolete. So, use of some microfabrication process is essential to develop the product. The first step in the fabrication is the selection of material for wafer. MEMS being a new area, the information about the properties and behaviour of most of the materials under certain operating conditions are still unknown [Rai-Choudhury, 1997]. So, if the use of the Silicon (the most common material) is not feasible due to any reason, then the material



F_i: Functions, DP_i: Design Parameters

Figure 3.5: Functional independencies [Suh, 1990]

selection becomes a very complex task and leads to uncertainty. For instance, if gallium arsenide is selected as a wafer material instead of silicon, then a thorough understanding of its physical and chemical properties is necessary to predict its behaviour with the etchants and also during other fabrication steps. Also, its compatibility with the material of the membrane must be investigated as they are to be joined at the end; see Section 3.3.3.

As mentioned in Section 3.3.3, one of the steps in developing the MEMS device is etching. There are several etchants available presently. But, the resulting shape of the etching process by large is unknown. It is very difficult to predict if the use of a particular etchant will serve the purpose or not. For example, in case of fluid chamber, if the material for the wafer is not silicon but aluminium, then the use of KOH will not achieve the desired feature. In that case, the use of PAN (phosphoric, acetic, nitric acids) will most likely achieve the desired features. If the selected etchant does not fulfill the purpose, either another etchant should be tried or the design of the chamber should be changed accordingly. Here it is important to mention that even a slight change in the design or development process requires the assessment of its impact from different disciplines. For example, the use of another etchant may have adverse effect on the wafer material like emission of harmful gases. To avoid that situation, the view from an expert of material science should be taken. With respect to the device in Figure 3.3, if the wafer material has to be changed, then there are certain issues that should be considered by the developer; (1) what will be the impact of change of material with respect to the other joining material?, (2) how the change in material will affect the mechanical properties like the surface tension and viscosity of the fluid?, (3) are the previous fabrication steps designed after the etching process still suitable or do they need to be modified?, (4) does the fabrication process require re-sequencing and scheduling? To answer these questions, the input from the experts from different disciplines is necessary so that the device functions satisfactorily. In this case, the change requires the view of experts from materials science, chemical engineering, mechanical engineering, and industrial engineering. In some cases, the impact of change in processes requires an assessment from the electrical point of view as well.

From the brief discussion above, it is inferred that the MEMS product development process is very complex and challenging in nature because of the high level of uncertainty involved in the outcome of the fabrication process. It is not possible for one person to acquire all the knowledge required for the development of MEMS products. This results in very high development time of MEMS products. There is a need of some computer support system to deal with such complex situations. The discussions in following chapters will explore the nature of MEMS development process and will illustrate the workflow management during MEMS development process.

3.5 Conclusion

MEMS product development is a highly complex task. To cope with the identified complexities, computer support to MEMS product development is necessary. The conventional computer aided design systems have not provided sufficient capabilities for MEMS product development in general. An essential problem with these systems is that they are unable to cope with the change of technologies and development environments (see Chapter 2). The next two chapters will present the idea and method to extend the existing computing technology to MEMS product development.

Chapter 4

MEMS Product Development Process

4.1 Introduction

In the previous chapter, the complexities associated with MEMS product development were explored by means of a case, i.e., the fluid dispensing system. These complexities were mainly characterized as highly multidisciplinary and highly uncertain in fabrication processes. So, an effective computer support is required to manage the MEMS product development process. In this chapter, the issue of managing MEMS product development process is discussed. It will be shown that the MEMS product development process resembles the so-called one-of-a-kind production (OKP) process. Therefore, the contemporary tools for managing the OKP product development process can readily be applied to the MEMS product development. The chapter is organized as follows: Section 4.2 discusses various models for product development processes in general. One-of-a-kind Production (OKP), which is a promising solution to the MEMS product development, is discussed in detail in Section 4.3. The characteristics of the MEMS product development process are elaborated in Section 4.4 to show how similar these two processes are. Section 4.5 shows how the contemporary modeling tools for the workflow management work for the OKP / MEMS product development process. Section 4.6 is a conclusion.

4.2 Models for Product Development Processes

The traditional model for product development process is sequential, where a set of design and manufacturing activities are executed in a sequential manner; see Figure 4.1. The problems with the sequential process are well known, such as (1) high development cost, and (2) poor reliability. The high development cost is due to the frequent backward and forward movements. The poor reliability is due to the frequent remedial actions on preceding designs while the design is moving on; in other words, there are repetitive processes with the philosophy of remediation.

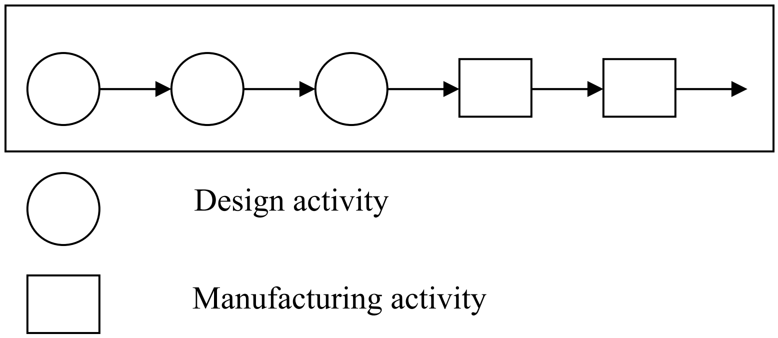


Figure 4.1: Sequential development process

Concurrent Engineering (CE) or concurrent design is an approach to organize design activities into more parallel processes. In particular, at each design phase, manufacturing and assembly feasibilities are reviewed and predicted; see Figure 4.2. Also, CE design tries to yield the structures such that manufacturing and assembly can be facilitated in light of low product cost and high functional reliability. CE has the benefits of reduced product development lead time and increased product functional reliability. However, CE is essentially about the design process, NOT about the manufacturing process.

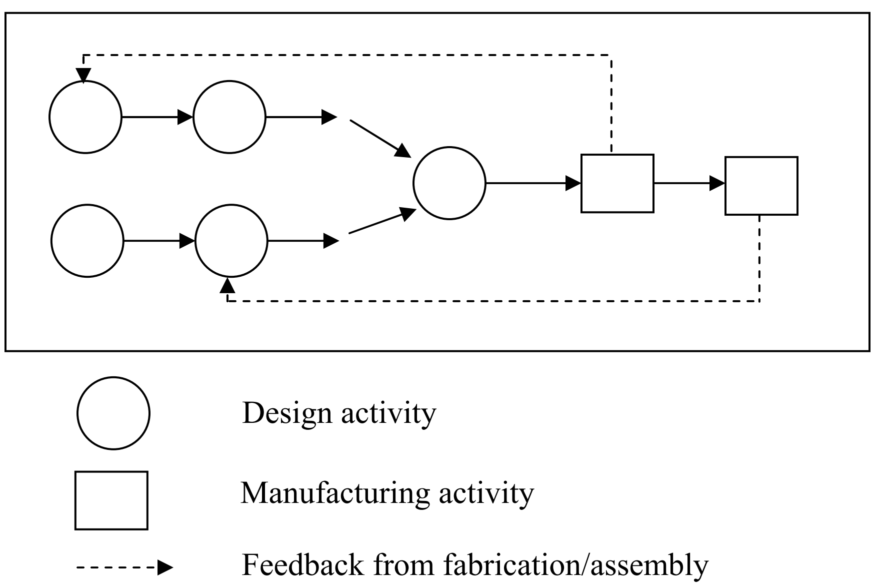


Figure 4.2: Concurrent engineering process

It is further noted that a design concept called modular design is closely related to the CE. This concept suggests that a product is designed based on architecture called modular architecture. In the modular architecture, a system is composed of a set of groups or modules [Zhang, 2001]. Components within modules are strongly coupled, while they are weakly coupled or not coupled with other modules. As such, the development of an entire product could then be divided into a set of development of modules, which can proceed in parallel.

4.3 One-of-a-Kind Production Process

In the sequential design process, the design proceeds serially; whereas the concurrent engineering approach mainly deals with the design rather than manufacturing. In some production cases, neither of these two processes seems suitable. For instance, in ship building, the design and the construction processes are interwined; see Figure 4.3. Physically, the result of the design and construction process is one product, i.e., a ship. In the manufacturing literature, such a product development process is called one-of-a-kind production (OKP) process [Wortman, 1991]. Many other product developments appear to have the OKP feature as depicted in Figure 4.3, e.g., the injection mold/tool development, process plant development, etc. One should notice that OKP does not necessarily correspond to one-batch production only; the important characteristic of OKP is the interwining among a set of design and fabrication/construction activities/phases (see Figure 4.3).

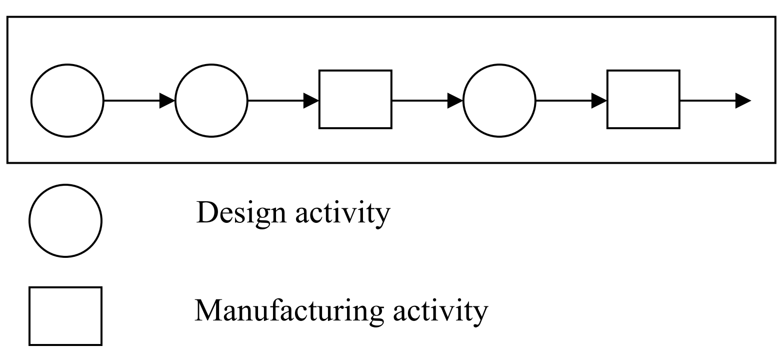


Figure 4.3: One-of-a-kind production process

While the OKP discussed above is somewhat ‘passive’ in the sense that the OKP process results from the development of a particular kind of product (e.g., the ship), there is a somewhat ‘active’ aspect with the OKP as well. The OKP process, as shown in Figure 4.3, implies a pattern - i.e., changes on a product under development can occur to as late as the end of a product development process. Application of this pattern can lead to a situation where the customer or the user of a product (which is a source of changes) can participate in the whole development process of that product. This means that customer’s needs could be possibly accommodated until the end of the development – an ideal customer-oriented product development strategy; see also the comment made by Wortman [1989]: ‘In the OKP system, continuous customer influence on production runs concurrently with product development and production.’ Another sense of the active aspect with the OKP lies in its adaptive property. The OKP process can be viewed as a highly adaptive process, where the concept of adaptive is two fold: (1) adaptive to fabrication / construction techniques and (2) adaptive to customer- induced change needs. This feature has a positive effect on the reduction of product development lead time, as the OKP philosophy advocates ‘trying to move’ even when fabrication techniques may be premature.

The OKP process is not without problem. One of the obvious problems is uncertainty in terms of quality, cost, and time of a product development. Such uncertainty creates challenges to the management of the OKP process. Such uncertainty results from (1) premature fabrication/construction techniques versus product delivery time; (2) uncertain availability of fabrication/construction techniques versus product delivery time; (3) uncertain availability of resources for product development, where resource means both the human resource and the infrastructure resource.

4.4 The Characteristics of MEMS Development Process

The most important characteristic of the MEMS development process is the uncertainty associated with the outcome of the fabrication processes. This can be attributed to the multidisciplinary nature of microfabrication technologies. For instance, a typical microfabrication technique called LIGA (German acronym for lithographe, galvanoformung, and abformung) integrates the disciplines including materials, electronics-based fabrication, molding technology, thermal dynamics, and fluid dynamics [Madou, 1997]. Prediction of the result of LIGA on a particular design feature is still very difficult. This is because of the fact that as the products are scaled for miniaturization, parameters such as temperature and fluid properties affect the performance of the product on a much larger scale compared to the macro scale (see previous discussions in Chapter 3). Besides, MEMS being a new area, information about properties and characteristics of most of the materials is still lacking. The wet etching technique may be another example of uncertainty in terms of both the function and quality achievable for a desired design feature. All these factors result in very long product development lead time of MEMS products. The other important characteristic of the MEMS development process is active reworking. The active reworking means that reworking is defined in a process plan during the progress of product fabrication. For instance, after etching of the chamber of the device discussed in Chapter 3, application of the photoresist on the backside of the wafer for etching to make the ejection aperture is planned; yet whether or not this process will eventually be followed will depend on the outcome of the etching. It may happen that the next step may not appear feasible or may not be required. In that case, the development process should search/look for some alternative way of fabricating the ejection aperture.

From the discussion so far, it is clear that neither the sequential development process nor the CE is suitable for MEMS products. The MEMS product development process resembles that of the OKP process. There is another evidence that the MEMS product development process resembles the OKP process. From a point of view of organization structure of a company (MEMS or OKP), the company usually relies on a set of partner companies or suppliers in such a way that the company plays a role as an integrator of technologies owned by its partner companies; see Figure 4.4. In that sense, such a structure of organization in company is called virtual organization or virtual company [Zhang, 1996].

Therefore, computer support tools for managing the OKP should be applied to the management of MEMS product development process. The next section introduces the current state-of-the-art of the process management for the OKP products with the objective of assessing whether the features of the OKP products are captured by these tools.

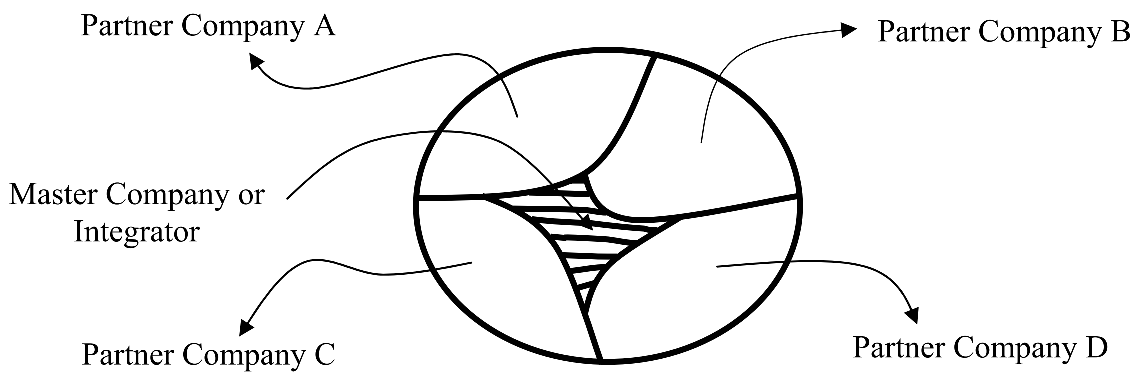


Figure 4.4: The concept of a virtual company

4.5 Modeling of the OKP Systems

4.5.1 General Concepts and History

From the point of view of control theory, the production or manufacturing system can be viewed as a time-varying system. Historically, models of production systems have been developed in stages, beginning with a mathematical model, such as a Markov chain or queuing model, or collection of models, and, if warranted, ending in a detailed simulation model. Markov chains work well for modeling and analysing small, well-defined, highly structured manufacturing systems such as flow shops and transfer lines. Queuing models can be applied to larger flow shops and transfer lines. Unfortunately, Markov chains and queuing models suffer from state-space explosion and limiting assumptions on arrival and processing time distributions [Gupta and Moore, 1996]. One approach to dealing with larger and more complex systems is to decompose them into subsystems, and develop independent Markov chain or queuing models of each subsystem. While this approach can be used to perform qualitative and quantitative analysis on the subsystems, it does not capture the interactions between the subsystems that make up the larger system. Hence, although the independent subsystems may perform as expected, the larger, integrated system may not operate correctly or efficiently [Gupta and Moore, 1996].

Petri nets (PNs) have recently emerged as a promising approach for modeling dynamic production systems like OKP [Jiang et al., 2001]. Petri nets are a graphical and mathematical modeling technique developed by Petri [1962] to model concurrent computer system operations. Since then, they have been extended and applied to a wide variety of systems [Murata, 1989]. The major advantages of PNs over Markov chains and queuing theory include: PNs can represent many states in a concise manner; PNs capture precedence relations and structural interactions; PNs can model deadlocks, conflicts, and buffer sizes; PNs can model multi-resource constraints; PNs have an underlying mathematical foundation that can be exploited to perform qualitative and quantitative analysis of the system; PNs can be directly converted into simulation models; and since PNs are derived from the logical sequencing of the system and are graphical, they are easy to understand and communicate to others. Appendix C includes information about PNs that is necessary to understand the discussion here. In the following discussion, it will be shown how a PN model can capture the features of the OKP system.

4.5.2 Petri Net Model for OKP Product Development Process

From the point of view of modeling, the generic feature with the OKP product development process is incomplete knowledge and information for the next time with reference to the present time. The conventional PN models will have to remodel the system whenever there is a change in a system. This does not suit the OKP situation. In order to let the PN model to work for the OKP situation, the model needs to have two extensions: (1) to allow a PN model to be extended and modified in real-time, and (2) to equip a PN model with the power to express fuzzy and uncertain information and knowledge. The example of fuzzy information could be as this: the next step of etching should apply higher voltage (here higher is meant for fuzzy information). The example of uncertain information could be as this: there is 90% success rate for the wet etching process to work for that particular feature.

Jiang et al. [2001] proposed a PN model which realizes the first extension (this model will be called the CPN-CS model in the following discussion). Their model is based on the Coloured Petri Nets (CPNs) with the addition of two structural modification operators on a PN model which are change-by-modification (CBM) and change-by-composition (CBC) respectively. CBM is the modification of the current structure elements, while CBC is the addition of a sub CPN into the CPN with the current structure. If changes to a system are made such that the model should be changed by both CBM and CBC, the model should be changed first by CBM and then by CBC (Here, it should be noted that the change of a CPN's structure does not necessarily require all the structure elements to change. The structure of a CPN is said to be changed if at least one structure element is changed). In the following discussion, an example with the features of OKP is used to illustrate how the CPN-CS model works.

Example 4.1:

Suppose a part membrane (M) is to be produced. There is a buffer B for both raw materials and finished products. The product states are indicated by M_i and the workstations are indicated by W_j, where i=9 and j=8 at the beginning. Initially, the process sequence is as follows:

$B \rightarrow M_1 \rightarrow W_1 \rightarrow M_2 \rightarrow W_2 \ldots\ldots W_8 \rightarrow M_9 \rightarrow B$

The PN model in this case is as shown in Figure 4.5.

Example 4.2:

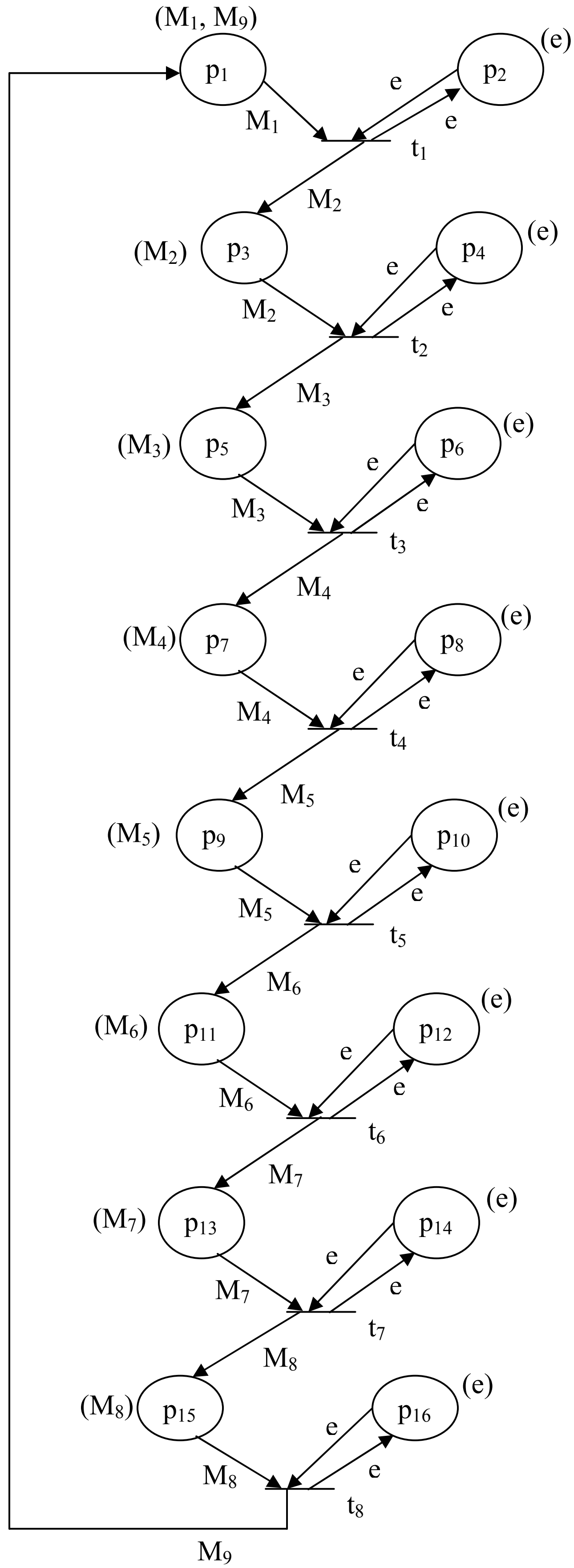
Suppose that in Example 4.1 there is a slight modification. While fabricating it is observed that part M_5 should be processed first at W_6 and then at W_5. In this case there will be a slight change in the model as shown in Figure 4.6 (CBM).

Example 4.3:

Suppose that in Example 4.2 it is further found that there should be a new workstation for radio frequency (RF) sputtering of thick titanium and thick gold before gluing the piezoelectric actuator for improved bonding and reliability. This can be done by adding the additional workstation. Hence, for this case, i=10 and j= 9. In this case, a sub-PN can be added to the original model as shown in Figure 4.7 (CBC).

4.6 Conclusion

The MEMS product development process resembles the OKP product development process. In order to model them, the PN theory needs to be extended to (1) allow a PN model to be extended and modified in real-time and (2) equip a PN model with the power to express fuzzy and uncertain information and knowledge. The PN model which was developed by Jiang et al. [2001], called the CPN-CS model, only fulfils the first extension. To further complete the second extension, integration of the CPN-CS model and the PN model with the power to represent fuzzy and uncertain knowledge and information is a solution.

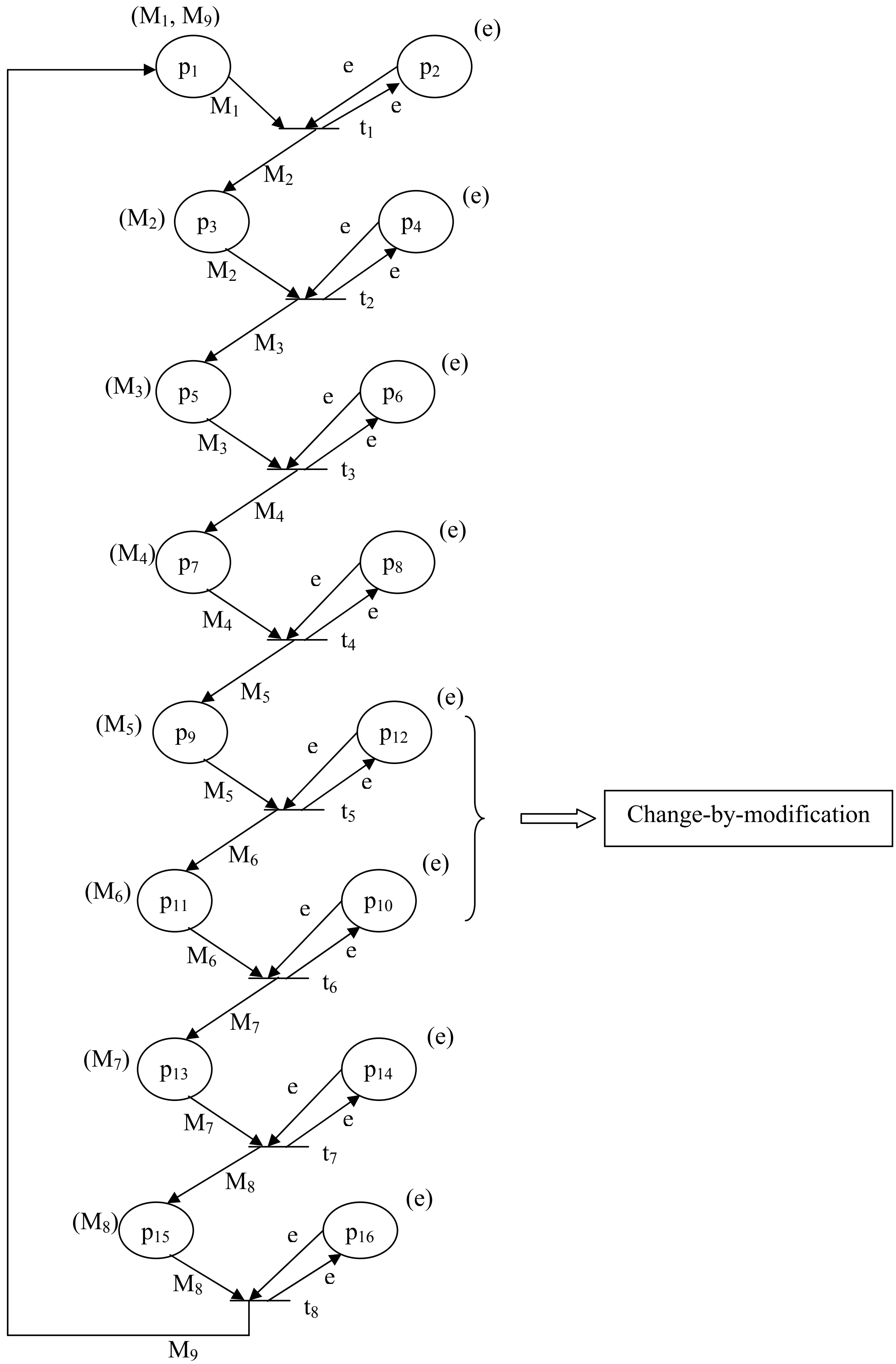

(M1, M9)
p1
p2
(e)
e
e
M1
t1
M2
(M2)
p3
p4
(e)
e
e
M2
t2
M3
(M3)
p5
p6
(e)
e
e
M3
t3
M4
(M4)
p7
p8
(e)
e
e
M4
t4
M5
(M5)
p9
p10
(e)
e
e
M5
t5
M6
(M6)
p11
p12
(e)
e
e
M6
t6
M7
(M7)
p13
p14
(e)
e
e
M7
t7
M8
(M8)
p15
p16
(e)
e
e
M8
t8
M9

p_1: Buffer for raw material (M_1) and finished products (M_9)
p_2: W_1 for cleaning the wafer
p_3: Part (M_2) ready for W_2
p_4: W_2 for coating the wafer with masking layer
p_5: Part (M_3) ready for W_3
p_6: W_3 for applying photoresist
p_7: Part (M_4) ready for W_4
p_8: W_4 for etching the masking part
p_9: Part (M_5) ready for W_5
p_{10}: W_5 for performing etching
p_{11}: Part (M_6) ready for W_6
p_{12}: W_6 for stripping the photoresist
p_{13}: Part (M_7) ready for W_7
p_{14}: W_7 for stripping the mask
p_{15}: Part (M_8) ready for W_8
p_{16}: W_8 for gluing the piezoelectric actuator
t_1: W_1 starts processing M_1
t_2: W_2 starts processing M_2
t_3: W_3 starts processing M_3
t_4: W_4starts processing M_4
t_5: W_5 starts processing M_5
t_6: W_6 starts processing M_6
t_7: W_7 starts processing M_7
t_8: W_8 starts processing M_8

Colour PM*= (M_1,……., M_9)
Colour E*= (e)
* PM: Product state of part M;
E: State of workstation (e-available)

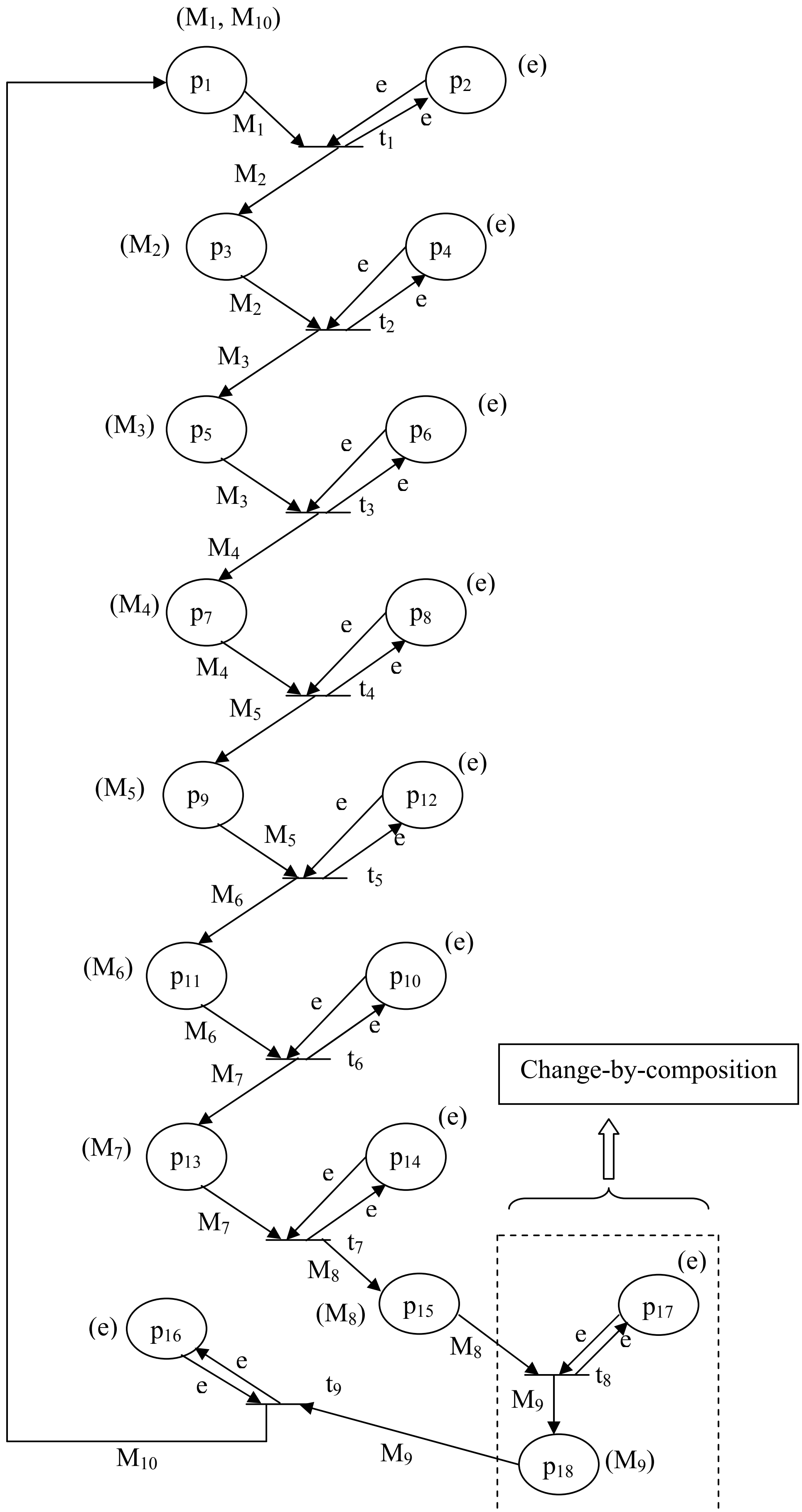
○ Place → arc
— Transition ( ) colour function

Figure 4.5: Petri net model for the Example 4.1


(M1, M9)
p1
(e)
p2
e
M1
e
t1
M2
(M2)
p3
(e)
p4
e
M2
e
t2
M3
(M3)
p5
(e)
p6
e
M3
e
t3
M4
(M4)
p7
(e)
p8
e
M4
e
t4
M5
(M5)
p9
(e)
p12
e
M5
e
t5
M6
(M6)
p11
(e)
p10
e
M6
e
t6
M7
(M7)
p13
(e)
p14
e
M7
e
t7
M8
(M8)
p15
(e)
p16
e
M8
e
t8
M9
Change-by-modification

p_1: Buffer for raw material and finished products (M_1 and M_9)
p_2: W_1 for cleaning the wafer
p_3: Part (M_2) ready for W_2
p_4: W_2 for coating the wafer with masking layer
p_5: Part (M_3) ready for W_3
p_6: W_3 for applying photoresist
p_7: Part (M_4) ready for W_4
p_8: W_4 for etching the masking part
p_9: Part (M_5) ready for W_6
p_{10}: W_5 for performing etching
p_{11}: Part (M_6) ready for W_5
p_{12}: W_6 for stripping the photoresist
p_{13}: Part (M_7) ready for W_7
p_{14}: W_7 for stripping the mask
p_{15}: Part (M_8) ready for W_8
p_{16}: W_8 for gluing the piezoelectric actuator
t_1: W_1 starts processing M_1
t_2: W_2 starts processing M_2
t_3: W_3 starts processing M_3
t_4: W_4starts processing M_4
t_5: W_6 starts processing M_5
t_6: W_5 starts processing M_6
t_7: W_7 starts processing M_7
t_8: W_8 starts processing M_8

Figure 4.6: Petri net model for the Example 4.2


(M1, M10)
p1
p2
(e)
M1
e
e
t1
M2
(M2)
p3
p4
(e)
M2
t2
M3
(M3)
p5
p6
t3
M4
(M4)
p7
p8
t4
M5
(M5)
p9
p12
t5
M6
(M6)
p11
p10
t6
M7
Change-by-composition
(M7)
p13
p14
t7
M8
(M8)
p15
p17
(e)
p16
t8
t9
M9
M10
p18
(M9)

p_1: Buffer for raw material and finished products (M_1 and M_9)
p_2: W_1 for cleaning the wafer
p_3: Part (M_2) ready for W_2
p_4: W_2 for coating the wafer with masking layer
p_5: Part (M_3) ready for W_3
p_6: W_3 for applying photoresist
p_7: Part (M_4) ready for W_4
p_8: W_4 for etching the masking part
p_9: Part (M_5) ready for W_6
p_{10}: W_5 for performing etching
p_{11}: Part (M_6) ready for W_5
p_{12}: W_6 for stripping the photoresist
p_{13}: Part (M_7) ready for W_7
p_{14}: W_7 for stripping the mask
p_{15}: Part (M_8) ready for W_9
p_{16}: W_8 for gluing the piezoelectric actuator
p_{17}: W_9 for RF sputtering
p_{18}: Part (M_9) ready for W_8
t_1: W_1 starts processing M_1
t_2: W_2 starts processing M_2
t_3: W_3 starts processing M_3
t_4: W_4starts processing M_4
t_5: W_6 starts processing M_5
t_6: W_5 starts processing M_6
t_7: W_7 starts processing M_7
t_8: W_8 starts processing M_9
t_9: W_9 starts processing M_8

Figure 4.7: Petri net model for the Example 4.3

Chapter 5

Knowledge Base for MEMS Products

5.1 Introduction

In Chapter 3, the need of a knowledge-based system (KBS) for MEMS product development was identified. This chapter presents a general methodology for building a design knowledge base in light of the need to have the flexible architecture of a KBS. This chapter is organized as follows: In Section 5.2, some basic concepts related to the architecture of a system are discussed. Section 5.3 discusses two key methodologies for a general knowledge-base system: the framework and template notions. Section 5.4 presents a knowledge framework which is based on a set of very generic concepts. In Section 5.5, a note is given on some difference between the framework proposed in this thesis and others. Section 5.6 presents a generic architecture of a knowledge-based system using the framework and template technologies. Section 5.7 justifies why the proposed architecture of a knowledge base meets the MEMS demand. Section 5.8 is a conclusion.

5.2 Basic Concepts

5.2.1 Architecture

In Webster's English dictionary [Webster, 1988], the *architecture* of *something* is defined as its *design and construction*. van der Wolf [1993] described the architecture of a system to be a description of its principal functions and global structures as seen from the outside, as well as a description of the principal mechanics of its inner structures. So the architecture of a system includes a description of (1) its main subsystems or objects, and (2) the ways they interact or exchange information.

5.2.2 Knowledge Base

Design needs knowledge. Knowledge should be structured for effective use. A knowledge base is a database of knowledge that is structured. A design knowledge base is a database of knowledge for design; while a manufacturing knowledge base is a database of knowledge for manufacturing. Because MEMS products are designed and manufactured in a highly integrated manner, a design knowledge base and a manufacturing knowledge base for MEMS should be integrated into one which may be called a development knowledge base. From a point of view of systems engineering, a knowledge base is a system. As such, it makes sense to say the architecture of a knowledge base.

5.2.3 General Design Knowledge Base

The goal of this thesis study was to devise a general design knowledge base. There are several meanings about the term *general*. First, the general means that the knowledge base can be used for or can be adapted to different applications. This is important to the MEMS product development due to its change nature in technology (see previous discussions in Chapter 3). Second, the general also means that knowledge base must be possibly extended in the sense that new design and manufacturing knowledge can be added. Third, the general means that a knowledge base must cover the whole design and manufacturing process. This requirement is important as it was shown in Chapter 3 and Chapter 4 that the boundary between different design phases in the conventional theory of systems design (conceptual, embodiment, and detail) and between design and manufacturing is 'blur' for the MEMS product development. In other words, a more integrated approach to the MEMS product development is necessary.

5.3 Key Methodologies for the General Knowledge Base System

The *first* key methodology is called the *framework* technology. The framework was defined as a set of concepts or modules that are generic or common for more than one system component; adapted from [van der Wolf, 1993]. The framework technology is thus to identify common building blocks (e.g., concepts, modules, etc.) for an underlying system. In general system design, the examples of building blocks are the notions of function, behaviour, structure, and state, because every system shares these notions. These notions will be discussed in detail later in Section 5.4.

The *second* key methodology is called the *template* technology. The template is defined as a predefined pattern, which is instantiated when the pattern is put in use. For instance, the following is a template (Template I):

Template I

Suppose that a gear is defined as having the number-of-teeth and pitch-diameter. This template can be instantiated as shown in Table 5.1. The template as just shown can be viewed as having a 'meta' structure with a guideline to instruct how to 'instantiate' the meta structure to eventually form a concrete structure. As such, the meta structure is

gear defined as: number-of-teeth, pitch-diameter

Table 5.1: Instantiation of the Component Gear

Gear	number-of-teeth	pitch-diameter (mm)
# 1	30	150.20
# 2	40	100.00

While the guideline here is such that each of the attributes defined in the meta structure gets a value, the instantiation of the meta structure following the guideline then results in two rows in Table 5.1. It should be noted that both the meta structure and the structure are knowledge.

The notion of the meta structure, the guideline, and the structure can be further generalized into the following three additional types of templates: Template II follows the data abstraction called the generalization/specialization; see Figure 5.1. The instantiation of Template II is therefore made along the generalization/specialization axis. For example, etching is a microfabrication process, and the instantiation of the etching template (Template II) is wet etching, dry etching, etc.

Template II

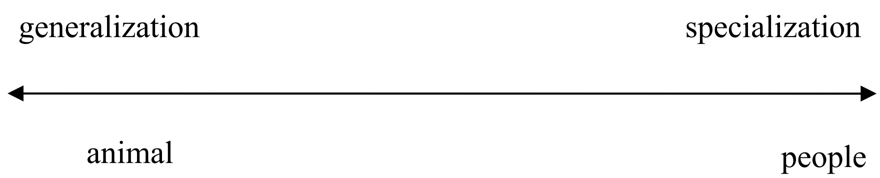


Figure 5.1: Generalization/Specialization Data Abstraction for Template II

Template III follows the data abstraction called the aggregation/decomposition; see Figure 5.2. For example, the gear has a module attribute, which is added alongside with the attributes: number-of-teeth and pitch-diameter. The instantiation of Template III is thus: the gear has the number-of-teeth, pitch-diameter, and a module. Template IV follows the data abstraction called the grouping or categorization; see Figure 5.3. It is noted that in Figure 5.3, the components, gear, cam, etc., are grouped into a higher level of data abstraction, i.e., the machine component. The grouping follows some membership rule. In case of Figure 5.3, the membership rule is: all instances, grouped as such, can act to transfer motion and force in certain unique ways. The instantiation of Template IV, is, thus, made by evaluating an instance against the grouping rule. Note that the definition of all these data abstraction notions can be found in Appendix D. The template concept can be further extended to a more complex situation; see the discussion in the next section.

Template III

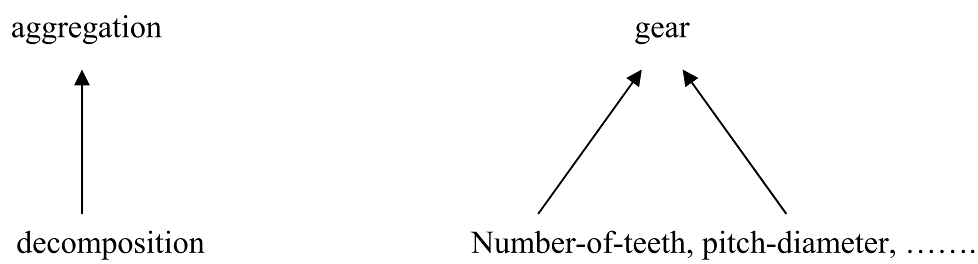


Figure 5.2: Aggregation/Decomposition Data Abstraction for Template III

Template IV

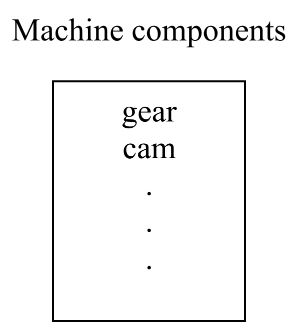


Figure 5.3: Grouping or Characterization Data Abstraction for Template IV

5.4 An Extended Function-Behaviour-Structure Framework

Design theory and methodology for general systems has been extensively studied in the past decades. Several well-known proposals of design theory and methodology include: Systematic Design Methodology [Pahl and Beitz, 1998], Axiomatic Design Theory [Suh, 1990], and the Integrated Bond-Graph and Function-Means Methodology [Bracewell and Sharp, 1994]. This thesis study pursued the direction of approaches which were based on the notions such as the structure, the behaviour, and the function. The knowledge representation along this direction may be called the Function-Behaviour-State (FBS) model. Pioneer studies on this model of design refers to [Gero, 1990; Rosenman and Gero, 1998; Umeda et al., 1990; Umeda et al., 1996; Chang et al., 2000].

The fact that there are variations in the definitions of the FBS model led to the development of the following alternative definitions. After that a note is given on the relation of the definitions here to others.

Structure and State

A system has a structure which is a set of entities connected in a meaningful way; see Figure 5.4. These entities are perceived in the form of their states when the system is in operation (see Figure 5.4). The states of the entities are thus quantities (numerical or categorical) of either physical or chemical domains. The states change with respect to time, which implies the dynamics of the underlying system. In order to systematically express the dynamics of the system, the states can be expressed by the variables called the state variables. In the following discussion, state variable may be interchangeably used with state.

The states are related in various ways because of the constraints imposed on the structure. These constraints come in two forms: the external and the internal. The internal constraints are those related to the connection between entities that form the system at time *t*. For example, in Figure 5.4, the fact that the membrane must be in physical contact at the location A but not B with the chamber has implied the constraint existed between the membrane and the chamber. The external constraints are those imposed from the environment to the entities of the system. For example, in Figure 5.4, the fluid flowing into the chamber has a certain pressure and temperature which are determined by entities out of the boundary of the system concerned.

In Figure 5.4, the state of flow rate at the nozzle is dependent on the opening of the nozzle, the flow rate at the inlet, and the actuation force applied to the fluid at the inlet. This shows that the state variable can be further divided into the independent state variable and the dependent state variable. For a particular system, its state variables and their dependencies are determined when the system is designed.

Behaviour

The behaviour of a system is about the response of the system when it receives stimuli. So the behaviour is the changes of states with respect to other states. This means that one may perceive the behaviour of the nozzle such that its behaviour is stated as: given the flow rate at the inlet $10\,m^3/s$ and the nozzle opening 30°, the flow rate at the outlet is found to be $5\,m^3/s$ (say). It should be noted that a system can be decomposed into sub-systems, components. The behaviour follows such decomposition. The behaviour of a sub-system may be such that at time 10 minute (after the whole system is put into operation), the opening of nozzle is 45°, the level of the fluid in the chamber is 2 mm, the flow rate at the inlet is $20\,m^3/s$, and the flow rate at the outlet is $10\,m^3/s$ (say).

Principle

The *relationships* among the state variables follow physical and/or chemical principles. For example, the relationship among the flow rate at the inlet and the outlet of the nozzle follows the principle that the flow rate is the product of the velocity of fluids and the area of a cross section (the flow rate principle). Relationships could be further related to more than two state variables. For example, the level of the fluid in the chamber (see Figure 5.4) is a state which is further related to the flow rate at the inlet of the tank and the flow rate at the outlet of the tank; so the principle governs a set of state variables and their relationships in particular. Because state variables are grouped in terms of components, sub-systems, and systems, the principles are associated with the components, sub-systems, and systems as well.

Function

A system has its function which is a subjective matter. The *function* is defined as a purpose in the mind of humans and can be realized by the system (structure) through the provision of certain behaviors by the structure. The function has two essences: (1) intensional and (2) extensional. The intensional part of the function is a total set of the 'qualified' behaviour of the system. The extensional part of the function is the instances of the intensional part of the function, purposely governed by 'effect.' The semantics of the function are given by an assertion which has the following syntactic form: Function := verb | noun | [proposition] | [value 1] | [proposition] | [value 2], where the notation '[ ]' means optional, and the notation ':=' means the assertion. For example, the function of a nozzle is to "eject the liquid at a specified flow rate (say 4nL/sec to 10nL/sec)", the function of the chamber (see Figure 5.4) is to "maintain the level of the fluid in the dosage chamber to a prescribed level."

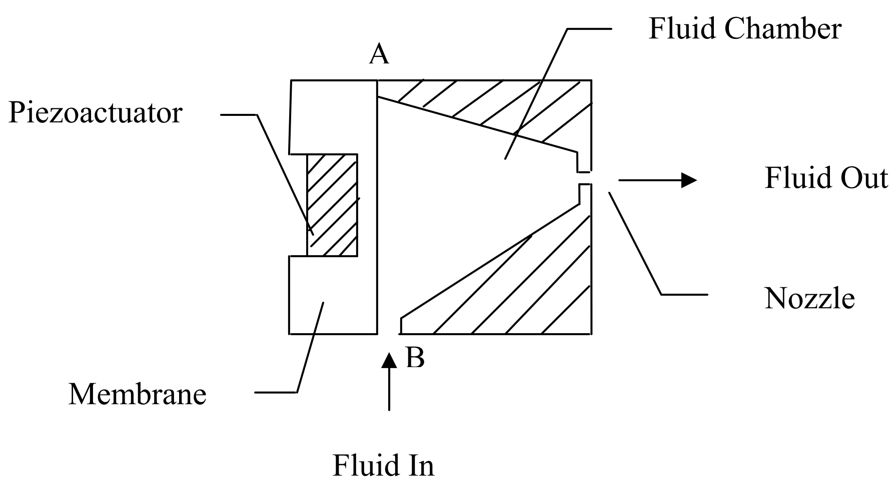


Figure 5.4: Piezoelectric-actuated drop-on-demand dispensing system

Effect

The effect is about the phenomenon that is observed in nature and society. The effect gives the rationale about why a particular behaviour can be used for a functional purpose. For example, one of the functions in the nano-litre dispensing process is to generate a high speed momentum of fluids such that the resolution of fluid drops is high. In this case, a functional reasoning process may undergo several steps (see Figure 5.5). A piezoelectric element serves as a behavior entity. It is known that when the electric charge is applied to the element, the element will deform to create high momentum based on the piezoelectric phenomenon. The high momentum itself takes as an effect leading to the nano-litre drop function.

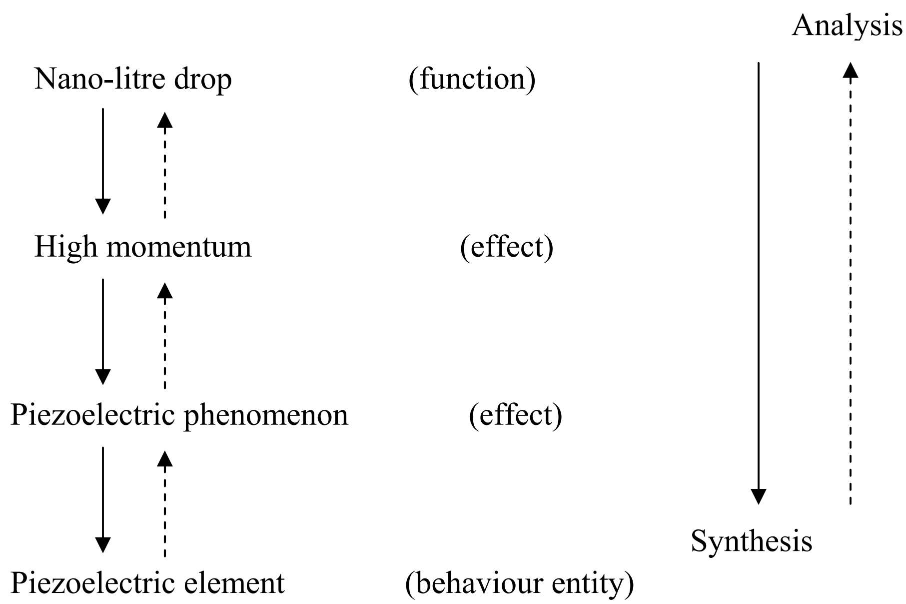


Figure 5.5: Role of the effect concept

The abovementioned concepts are further related to each other, as shown in Figure 5.6. The principle concept stays between the state and the behaviour to give the constraints such that given a set of (independent) states, dependent states are found through the evaluation of the constraints. The effect part stays between the function and the behaviour to provide inference path from the behaviour to the function as illustrated in Figure 5.5.

The design process that goes from the function to the structure is called synthesis Figure 5.5). The synthesis process is qualitative in nature. The design process that goes from the structure to the function is called analysis (Figure 5.5). The analysis process is quantitative in nature. Following the notion of the template, the structure shown in Figure 5.6 can be considered as a general design template too, which is called the function-effect-behaviour-principle-structure-state (FEBPSS) template. Later in this chapter, there is a discussion about the application of the FEBPSS template for several design situations.

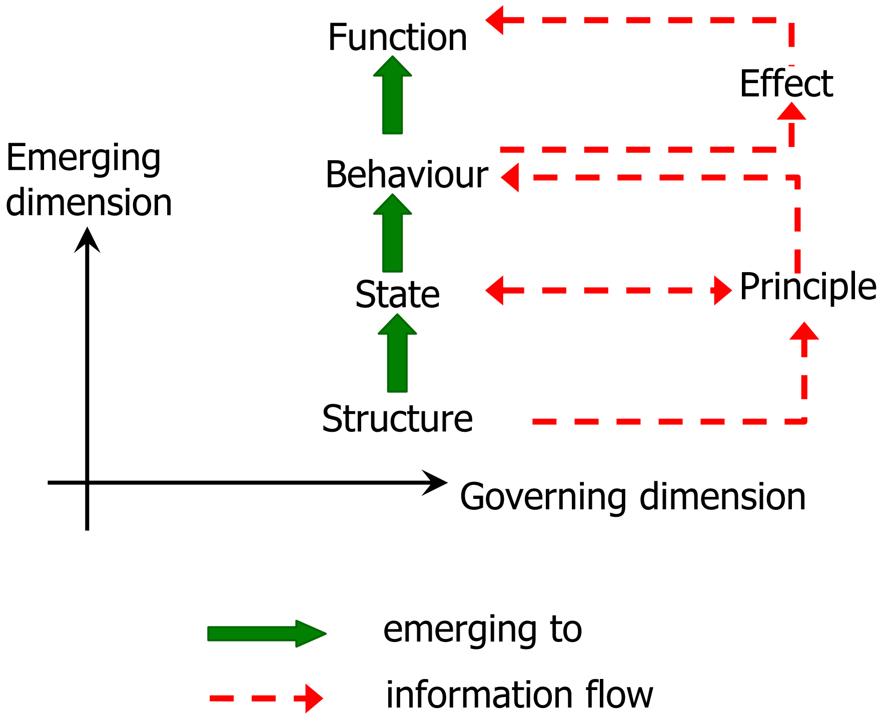


Figure 5.6: The FEBPSS framework

5.5 A Note on the Relation of the FEBPSS Framework to Related Studies

There are several schools of function-behaviour-structure models for design (see previous discussions in Chapter 2 also). Rosenman and Gero [1998] proposed four layers of concepts; purpose, function, behaviour, and structure; whereas Umeda et al. [1990] and Chang et al. [2000] argued that only three layers (i.e., function, behaviour, and structure) are sufficient for designing a system. According to Rosenman and Gero [1998], the purpose concept is an intended function and hence is a subset of function. On the other hand, according to Chang et al. [2000], the function is a subset of behaviour. So, confusion arises from these two views.

There are several distinct points between the FEBPSS framework and those others. First, the FEBPSS framework explicitly includes the principle and effect concepts. Absence of these two concepts in a knowledge representation will produce an incomplete knowledge with respect to the computer. In other words, knowledge of the principle and effect has to be maintained in the designer's mind. Second, the FEBPSS framework explicitly distinguishes the structure from the state, whereas others have only described them vaguely. In particular, usually only the structure concept is explicit in others' studies; e.g., [Umeda et al., 1990]. When the behaviour of a system is qualitatively evaluated, the state variable concept must be in knowledge base.

5.6 General Knowledge Base for MEMS (GKB-MEMS)

5.6.1 Architecture

Based on the discussion above, architecture of a general knowledge base for MEMS (GKB-MEMS for short) is proposed. GKB-MEMS takes the FEBPSS framework as a backbone. This backbone references to individual knowledge bases, i.e., function knowledge base, effect knowledge base, principle knowledge base, behaviour knowledge base, state knowledge base, and structure knowledge base. Individual knowledge bases follow the template technique as discussed before. In general design theory and methodology, design has various different types, such as conceptual design, embodiment design, detailed design, and modular design. They refer to specific situations of the GKB-MEMS; in particular the FEBPSS framework will omit some concepts. For instance, for the so-called conceptual design where only solution principles are concerned, the FEBPSS may only have the function concept, the effect concept, and the behaviour concept.

Principles for representing knowledge using these templates (I, II, III, IV, and FEBPSS) are discussed as follows. The first principle is regarding the identification of a piece of knowledge. Each piece of knowledge will get a unique identification (ID for short). The ID is also used as a means of reference among various pieces of knowledge. Figure 5.7

depicts an example, where the gear concept appears in the knowledge definition for the machine component concept based on Template IV, which it is defined, based on Template III as having attributes: number-of-teeth and pitch-diameter. Furthermore, it is also shown in Figure 5.7 that a particular gear in reality (i.e., in some design catalogue) #G01-001 is defined based on the Template I. Specifically, this gear has 32 teeth and its pitch diameter is 35.75.

The second principle for the representation of knowledge using the template techniques is that both data and its context information are specified. This is an important point, yet not stated in the literature except [Zhang, 1994]. In his doctoral thesis work, Zhang [1994] has proposed the information relativity principle in which he stressed the need to represent both data and their contexts, as the semantics of the data makes sense within a particular context. The third principle is the explicit specification of the types of templates. This information gives the direction to interpret the data. Figure 5.8 shows a conceptual representation, which is based on the three principles as described before.

The example of the piece of knowledge about the gear component, as shown in Figure 5.7, is illustrated in Figure 5.9, based on the conceptual representation as shown in Figure 5.8.

In the following, an example is given for the representation of the FEBPSS framework. Note that the FEBPSS can be viewed as a template too. Let us denote the FEBPSS template as Template 0. Furthermore, Template 0A: The FEBPSS contains only the function, effect, and behaviour concepts; and Template 0B: The FEBPSS contains only the function and structure concepts.

Assume that design in this case is at the conceptual design phase. The FEBPSS template contains only the function, effect, and behaviour concepts. Further assume that in this case the function is to achieve a high momentum motion so that the nano-litre quantity of fluids can be generated. To fulfil this function requirement, the piezo-electric effect is chosen. This then leads to the behaviour entity, i.e., the piezo-actuator. Figure 5.10 shows the representation of the knowledge as just described.

It is important to represent a general formula of knowledge, which is usually called production rule. This formula has the format:

Cause statements → Action statements

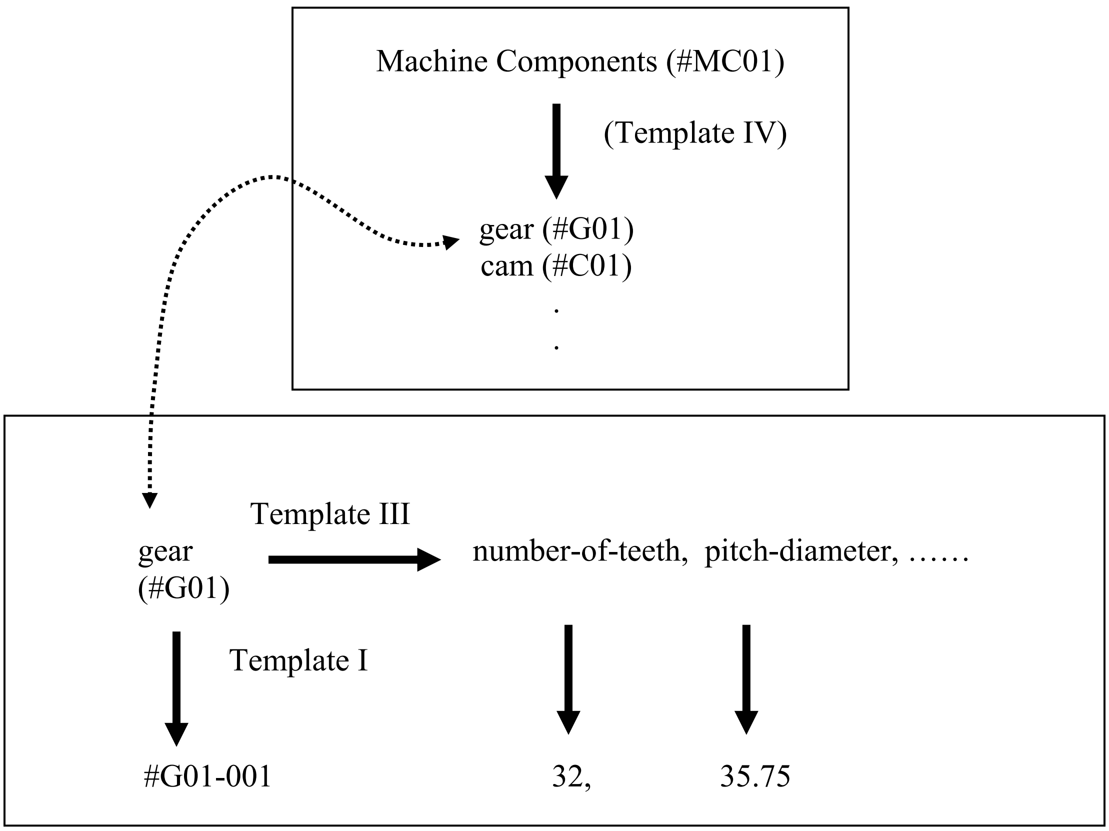


Figure 5.7: Knowledge identifier and its role

The cause statement contains several sub-statements, which contain logic variables and their values. The production rule can have two types of uses: (1) for synthesis, and (2) for analysis. In the case of synthesis, the function is in the cause statement, while the

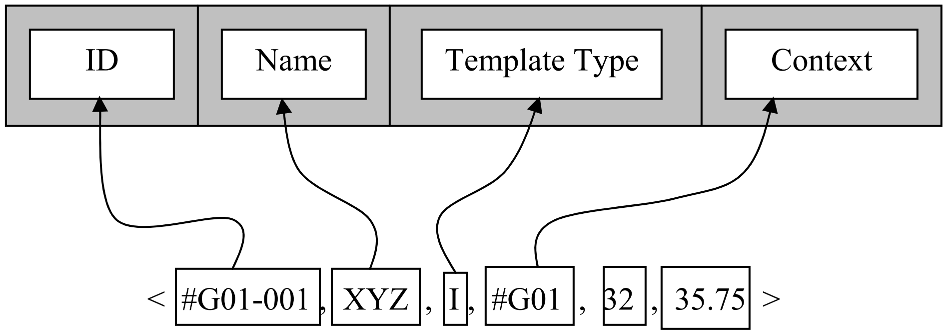


Figure 5.8: A conceptual representation of knowledge using the proposed template technique

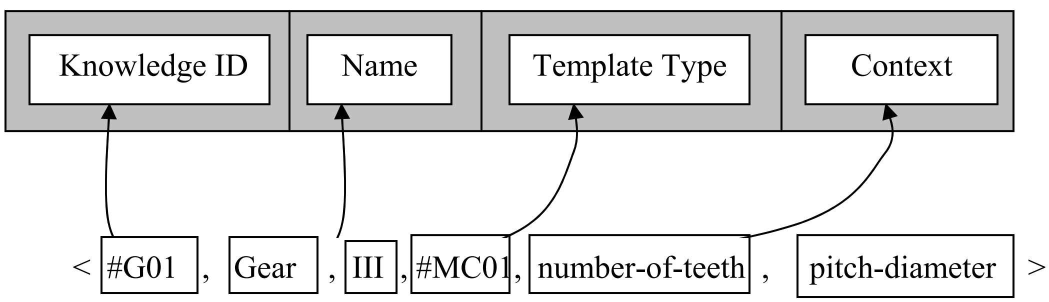


Figure 5.9: An example of the knowledge representation

< #FEB01[1], Piezo-electric, 0A, FEBPSS, #F01[1], #E01[1], #B01[1] >

< #F01, high-momentum-motion, III, _, momentum[2] >

< #E01, piezo-electric-effect, I, Physical effect (#PH02), description[3] >

< #B01, piezo-actuator, III, _, voltage, deformation >

Note: (1) #FEB01, #F01, #E01, #B01 are knowledge identifiers respectively.

(2) Momentum is an attribute with its domain as a set of real numbers.

(3) Description represents the piezoelectric phenomenon.

Figure 5.10: Template representation of knowledge in conceptual design phase

structure (or solution) is in the action statement. In either of these cases, the FEBPSS template will reduce to having two concepts, i.e., the function and structure concepts.

5.6.2 Dynamics of GKB-MEMS

Design can be viewed as a decision process in which the designer applies pieces of knowledge in a knowledge base and makes decision to fulfill requirements (functions and constraints). In a computer aided context, this process can be viewed as a set of action pairs (put and get data); see Figure 5.11. It should be noted that both the product in progress and the knowledge in the knowledge base are represented by the templates as developed earlier. This idea has the following benefits. First, the management of both information units is simplified owing to one formalism. Second, data in the product-in-progress repository are knowledge or information too. So, they may be used for subsequent designs of the same product, or design of other similar products. For example, suppose that there is a description of many etching techniques in the knowledge base, and at the time of current product development, some new technique has been devised and used. The new technique can be added to the knowledge base for use in future product development. Using the same template technique, the transfer of more knowledge or information from the product-in-progress repository to the knowledge base is straightforward; see Figure 5.12. It is further noted that this idea is very useful to

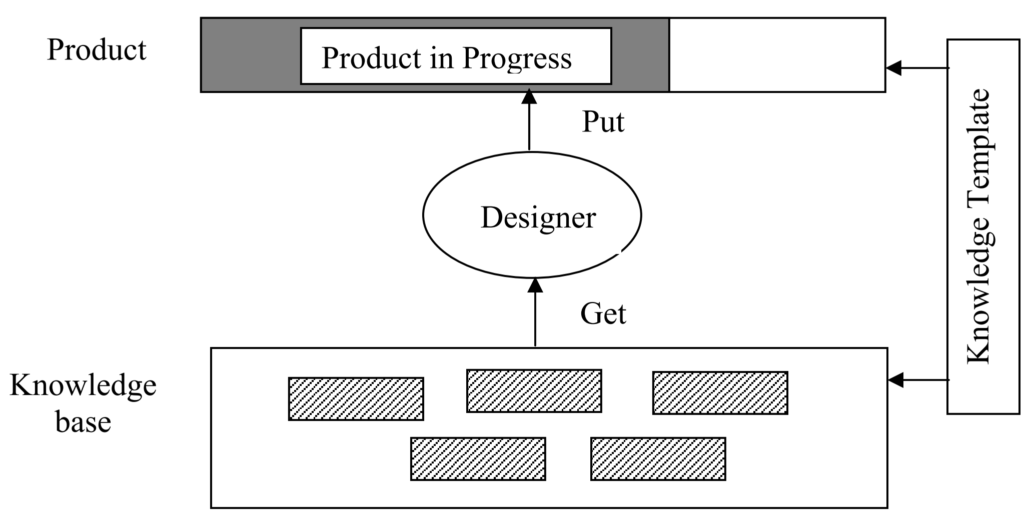


Figure 5.11: Computer aided design process as a set of action pairs

MEMS product development, as the creation and deletion of a piece of knowledge should be a frequent need in MEMS product development- a result from uncertainty in the microfabrication process.

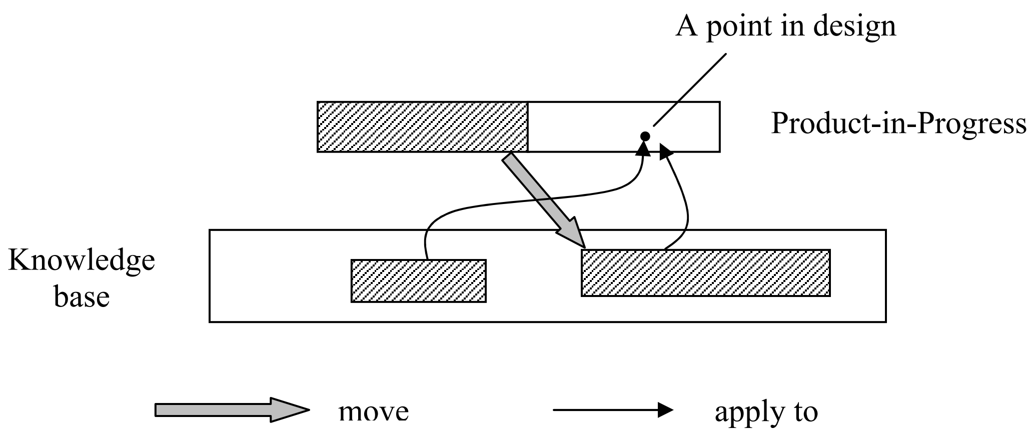


Figure 5.12: Transfer of knowledge from product-in-progress repository to the knowledge base

5.7 The GKB-MEMS Vs. MEMS Product Development

Design is generally separated into the following phases: design specification development, conceptual design, embodiment design, and detailed design. The design specification clarifies design requirements. The conceptual design determines the principles of solutions or solution concepts. The embodiment design determines the structure (overall layout) of a technical system in line with technical and economic criteria. The detailed design generates the engineering drawing which includes the tolerance information, material information, and some general directions of fabrication and assembly. The GKB-MEMS can be adapted to all these design processes; see Figure 5.13. A design may not undergo through all these phases, which means that sometimes design may not explicitly include the detailed design (e.g., the modular design process). The GKB-MEMS can support this by selecting proper concepts within the FEBPSS framework (see previous discussion in Section 5.6). So, the GKB-MEMS can fulfil the requirement for a general knowledge base.

The GKB-MEMS is very flexible as it is easy to include or exclude a template in GKB-MEMS. For instance, if one wants to add a new effect, e.g., thermal-deformation effect, into the GKB-MEMS, one need to proceed with the following steps.
Step 1. Create a knowledge id (which should be unique to an existing GKB-MEMS, e.g., #E005.

Step 2. Browse the knowledge base, in particular the physical effect knowledge base, and write

< #E005, thermal-deformation, I, #PH02, description >

It is further noted that the template technique as described is very similar to the modularization technique. This is the reason why the GKB-MEMS offers a flexible architecture for knowledge base, which fulfills the requirement for MEMS product development.

Design phases		**FEBPSS template**
Design specification	↔	customer needs, function
Conceptual design	↔	function, effect, behaviour
Embodiment design	↔	principle, behaviour, state, structure
Detailed design	↔	state, structure

Figure 5.13: A comparison between GKB-MEMS and the design phases

5.8 Conclusion

In order to meet the demand of an effective computer support for MEMS product development, there is a need to have a general and flexible knowledge base. This chapter presented an approach to such a knowledge base, which is called GKB-MEMS. The key method to make the GKB-MEMS meet the MEMS demand is the two notions: the framework and the template. While the framework notion is more philosophical or conceptual, the template notion is more representational, which resembles the modularisation notion in hardware product development. Specially, a set of core concepts, function, effect, behaviour, principle, state, and structure, are put together to form a backbone in the GKB-MEMS. Together there are five general templates for knowledge representation. The template technique with the FEBPSS framework seems sufficient to meet the MEMS demand.

Chapter 6

A Case Study

6.1 Introduction

This chapter is intended to demonstrate how the proposed approach to knowledge base development in Chapter 5 can be applied to a design example. The design case for the purpose of illustration here is a fluid dispensing system presented in Chapter 3. There are two focuses in this chapter: (1) to illustrate further how a specific GKB-MEMS is built, and (2) to illustrate the design process, which incorporates GKB-MEMS for MEMS products. The chapter is organized as follows: In Section 6.2, the design case explained in chapter 3 is revisited. Section 6.3 describes the knowledge base template specifically for the microdispensing system. Section 6.4 shows how the knowledge base helps to proceed with the design of this device. Section 6.5 summarizes the design result. Section 6.6 consists of a conclusion.

6.2 Design Case: Revisit

The purpose of revisiting the design example discussed in Chapter 3 is to discuss in detail various specific technical issues that should be considered while designing this device.

6.2.1 General Description

From customers' point of view, following is a list of requirements for this device:

- It should have high efficiency. In other words, it should dispense an adjustable amount of small droplet fluids in a given time;
- It should be reliable over a long period of time;
- It should have a uniform flow rate, especially when used for medical applications;
- It should be environment friendly;
- It should be as small as possible; and

- It should be available at low cost.

6.2.2 Technical design specification

From the engineering perspective, the above needs of the customers are converted into following technical forms.

Fluid properties

As discussed in Chapter 3, the technical issues in fluid properties include viscosity, surface tension, capillarity, presence of particulates in the fluid (that block the nozzle), fluid's compatibility with the dispenser's material, its behaviour when exposed to air, and its stability with time. These issues are discussed in detail here.

Viscosity is an important internal property of a fluid that offers resistance to flow. The fluid must not be so viscous that it cannot be jetted. Different materials have different viscosities and they are used to predict behaviour and to compare one material to another. When temperature increases, viscosity decreases. There is an optimal viscosity range for fluid dispensing systems to produce reliable monodisperse drops at high ejection rates. In practice, combining together compatibly miscible solvents with different viscosities, such as glycerol and water, most often sets viscosity. Most of the viscosity modifiers are polyhydric alcohols. In general, viscosity in the range of 1-30 cS makes fluids ejectable with high stability [Lee, 2002].

The cohesive forces between liquid molecules are responsible for phenomenon of *surface tension*. The molecules at the surface do not have other like molecules on all sides of them and consequently they cohere more strongly to those directly associated with them on the surface. This forms a surface "film" which makes it more difficult to move an object through the surface than to move it when it is completely submersed. This phenomenon is known as surface tension. In general, surface tension in the range of 20-60 dynes/cm makes fluids ejectable with high stability.

Capillarity is a phenomenon associated with surface tension and results in the elevation or depression of liquids in capillaries. It occurs as a line force in gas-solid-liquid interface and can be expressed as

$$F_{cap} = L\gamma Cos\theta_c$$

where L is the length of the interface line, γ is the surface tension coefficient, and θ_c is the wetting angle. Control of liquid in a microsystem thus requires control of the capillary forces that are present.

Surfactants are added to dispensing fluids to alter the surface tension and contact angles to more optimal values for stable droplet ejection. Optimizing the surface wetting characteristics of fluid with different parts of the drop ejector is important. If the fluid does not wet the inside of the fluid reservoir and the ejection hole easily, the drops may not form, the air may be difficult to purge from the system during the fill operation, and the fluid refill time of the ejection aperture may be slow enough to compromise frequency of operation. Surfactants for this reason are typically added in fractions of a percent of the total volume of the fluid.

In addition to the above-mentioned fluid properties, the fluid should not contain particulates that are large enough to jam the fluid ejection hole. It should not change due to exposure to the air. It should be compatible with the drop generator's material and dispensing process, and most importantly it should be stable with time.

Drive Pulse Amplitude

In Chapter 3, it was stated that too high or too low drive pulse amplitudes are not good for proper functioning of the microdispensing system. This is because at amplitudes below the threshold of drop ejection, a fluid jet is ejected and drawn back on the negative pressure cycle of the pressure excitation. If the amplitude is too small, then fluid jet will be completely withdrawn into the chamber. If the amplitude is too large, then multiple drops will form producing satellite drops. Within the safe driven voltage range, increasing the drive amplitude both increases the size of the drop and the ejection velocity. Some relations related to amplitude that are useful while setting the parameters are

i) Drive amplitude $\propto$ Viscosity

ii) Drive amplitude $\propto$ 1/area of the disc

Drive Pulse Shape

The pulse shape of the waveform used to excite a piezoelectrically actuated fluid dispensing system has wide-ranging effects on the drop ejection process. The tuning of a particular fluid dispensing system design for a given fluid by optimizing the drive waveform is a critical part of setting up a fluid dispensing system. A non-optimal drive waveform can be the cause of noninjection, ejection of misdirected drops, and ejection of drops with unwanted accompanying satellite drops. Following is a list of some general information used for tuning of the dispensers:

i) Pulse widths between 0.5 microseconds and 10 microseconds have been found to be the most often used range for large reservoir piezoelectric disc driven dispensers,

ii) Shorter pulse widths tend to produce smaller drops,

iii) Shorter pulse widths tend to require higher amplitude to eject drops,

iv) Tuning of the pulse width can produce drops of half the nozzle hole diameter to twice the nozzle diameter (although the drop-size is primarily determined by the size of the ejection aperture nozzle hole), and

v) Changing the pulse width can sometimes affect the directional stability of the ejected drops.

Internal Pressure Level

Another aspect important for the operation of drop-on-demand dispenser is the behaviour of fluid near the hole in the ejection aperture, which in turn depends on the internal pressure level. Misset internal pressure can disable drop production. The level of internal negative pressurization needs to be tuned to the fluid used and the size of the ejection aperture. This is because the optimal negative internal pressurization of the dispenser reduces the pulse energy needed to eject drops and, in general, increases ejection reliability. There are following points that should be paid proper attention:

i) Insufficient negative pressure can cause fluid build-up over the meniscus hole,

ii) Too negative internal pressure will draw in air bubble,

iii) High surface tension fluids with high contact angles with the ejection aperture external surface may need no negative pressurization at all to operate,

iv) Drop generators with large diameter ejection holes require a more precise setting of the negative internal pressurization,

v) If the fluid's internal pressure is sufficiently high, a continuous stream of fluid can be ejected.

Drop Ejection Rate

In order to have a reliable operation, there should be a maximum and minimum stable ejection rate. Some fluids deposit a small amount of residue on the outside of the aperture during each ejection cycle. Fluids, which leave a solid residue when evaporating, require a minimum amount of energy for ejection if the fluid is not moved actively for certain period of time. In inkjet printing literature, it is known as the 'first drop problem.'

On the other hand, at very high rates, this externally deposited fluid can build up faster than it can evaporate away or be drawn by negative internal pressurization back into the chamber. Also, at very high rates, heating of the fluid can change its viscosity. In extreme case, the heat can depole the piezo drive element and break down or boil the ejection fluid. This comes from both absorption of energy in the fluid and conductive heat transfer from the drive elements.

Fluid Temperature

The dispensing characteristics of some of the fluids can be significantly enhanced by operation at elevated temperatures. This is because rise of temperature in a fluid does not affect surface tension considerably but has larger effect on the viscosity. As discussed earlier, the viscosity of the fluid decreases with the increase of temperature. This reduces the drive energy required for dispensing the fluid. Also, the reduction in fluid viscosity enhances operation by suppressing satellite drop formation.

Material Compatibility

All the materials selected for fabrication should be compatible with each other. This fact was stated in Chapter 3. It should be investigated if two different materials have good bonding properties and if they react with each other or with etchants during fabrication or in operation to produce some harmful products. For example, the nozzle material and the dispensing fluid should be compatible for smooth ejection of the fluid.

Structure Strength

The system should have enough strength to survive stresses, fatigue of the membrane, and friction during operation. Also, it should not be susceptible to corrosion by the fluid.

The following discussion focuses on the functional requirement for the purpose to illustrate how the knowledge base model proposed previously can be useful to support the development of MEMS products.

6.3 Knowledge Base Template Specialized for Microdispensing System

The knowledge base template developed in this section is specialized for the microdispensing system. This specific template is built upon the generic template developed in Chapter 5. In this thesis, the design is restricted to the conceptual design phase. This implies that the FEBPSS template will contain only the function, effect, and behaviour concepts; see Chapter 5.

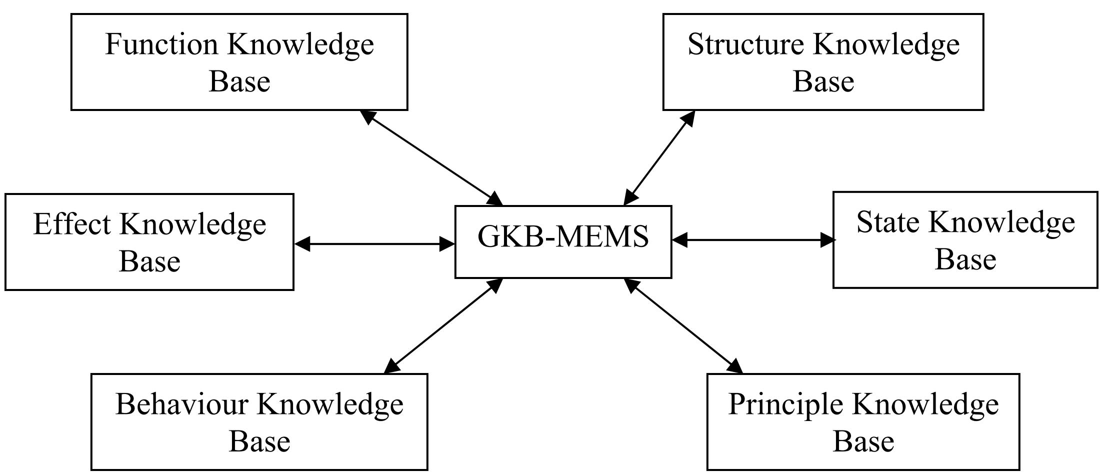


Figure 6.1: Interaction between GKB-MEMS and individual knowledge bases

As illustrated in Chapter 5, the GKB-MEMS takes the FEBPSS framework as a backbone, and this backbone references to individual knowledge bases. This is shown in Figure 6.1. The knowledge in each of the individual knowledge bases can be represented by following the principles explained in Chapter 5. For example, the sample knowledge in the case of a microdispensing system using templates is shown in Figure 6.2. On the top, the knowledge of fluid dispensing is specialized into the microdispensing, and the microdispensing system is further specialized into the piezoactuated microdispensing system; see block 1. The knowledge (#MD01) references to the knowledge block 2, which contains several components of a microdispensing device. In the knowledge (#MD01), the nozzle component further references to block 3 where the concept of nozzle is defined in detail. The conceptual representation of the knowledge using the proposed template technique is shown in Figure 6.3.

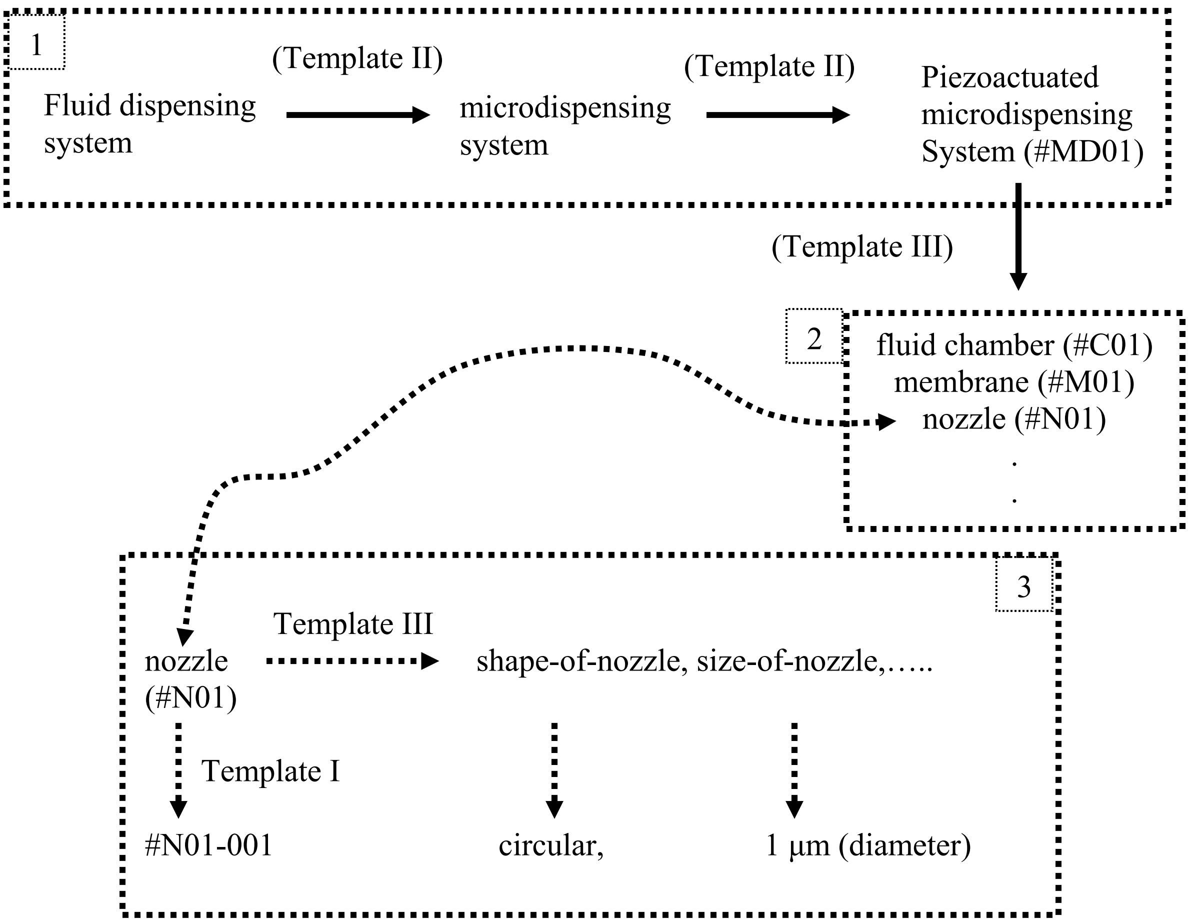


Figure 6.2: Sample knowledge for the microdispensing system

To develop an extensive knowledge base template, the first task is to list all the functional requirements, effects and behaviours of the microdispensing system. The next task is to express all the functions and their corresponding behaviours and effects in the template form in the respective knowledge bases. For example, the main functional requirements of the microdispensing system are: (1) to achieve high momentum motion for micro-litre fluid generation, (2) to have uniform flow rate; (3) to operate with high degree of reliability; and (4) to work in an environmentally friendly manner. The template representation of knowledge for these functions that may be stored in a function knowledge base is shown in Figure 6.4. Similarly, the templates for the other two knowledge bases are shown in Figures 6.5 and 6.6, respectively.

< #N01-001 , nozzle , I , # N01 , circular , 1 µm >

Figure 6.3: A conceptual representation of knowledge for the nozzle

Function Knowledge Base

< #F01, high-momentum-motion, III, _, momentum >

< #F02, uniform-flow-rate, III, _, flow-rate >

< #F03, high-reliability, III, _, reliability >

< #F04, environment-friendly, III, _, environment-friendliness >

< #F05, etching, III, _, material-removal >

…………..

- Context information is not concerned

Figure 6.4: Function knowledge base for the microdispensing system

Effect Knowledge Base

< #E01, piezo-electric-effect, I, Physical effect (#PH02), description >

< #E02, electrostatic-effect, I, Physical effect (#PH02), description >

< #E03, thermal-deformation-effect, I, Physical effect (#PH02), description >

< #E04, uniform-flow, I, Physical effect (#PH03), description >

< #E05, high-strength, I, Physical effect (#PH04), description >

…………..

Figure 6.5: Effect knowledge base for the microdispensing system

Behaviour Knowledge Base

< #B01, Piezo-actuator, III, _, voltage, deformation >

< #B02, electrostatic-actuator, III, _, electric field, deformation >

- Context information is not concerned

< #B03, thermal-actuator, III, _, heat, deformation >

< #B04, flow-parameter, III, _, viscosity, surface-tension, drive-pulse-amplitude, drive-pulse-shape, fluid-temperature, internal-pressure >

< #B05, strength-parameter, III, _, stress, friction, corrosion, chemical-reaction, bonding, fatigue >

…………..

Figure 6.6: Behaviour knowledge base for the microdispensing system

The following section will explain how the knowledge base designed above helps in the development of this device.

6.4 Use of Knowledge Base Template for Design of the Device

As explained in Chapter 5, the computer aided design process for MEMS products can be viewed as a set of action pairs, which consist of getting and putting data. During MEMS product development, two databases for storing knowledge and information are around: one for storing the proven knowledge that is ready to use, and the other for storing design and fabrication states. The first database may be called the design knowledge database, and the second one called the product-in-progress database. The designer extracts knowledge from the design knowledge database, applies it to his or her problem at hand, makes decisions on the problem, and inserts the decisions in the product-in-progress database. The designer's activity is supported by the computer program which is yet not a fully automated one. In the following, the designer's activity in conjunction with the computer program that implements the design knowledge base model is illustrated.

Suppose that the function of the device is to achieve a high momentum motion to generate micro-litre amount of fluids. In the design knowledge base, there is a function knowledge base (see Figure 6.4). The scenario where the designer exploits the design knowledge base may be such that the designer enters the phrase 'high-momentum-motion' to the program. The program picks up this phrase and searches the function knowledge base. It is expected that the search will hit one piece of knowledge in the function knowledge base, i.e.,

< #F01, high-momentum-motion, III, _, momentum >

It is also possible that the program guides the designer to browse the function knowledge base, and the designer spots one piece of knowledge that fits his or her need of the function. These different scenarios are the matter of computer implementation of the knowledge base model as described before. It is noted that the program then picks up the hit function 'high-momentum-motion', in particular, its knowledge id (#F01) and searches the FEBPSS knowledge base, for example, the framework template 0A, as described above. One instance in the FEBPSS 0A knowledge base is hit, i.e., the one as follows:

< #FEB01, Actuation, 0A, FEBPSS, #F01, #E01, #B01 >

This instance after retrieved, tells the designer the effects (#E01) and the behaviour (#B01) that realizes the function (#F01).

Next, the designer refers to the effect knowledge base (see Figure 6.5) to find some detail about the effect (#E01). The effect knowledge base provides the following:

< #E01, Piezo-electric effect, I, Physical effect (#PH02), description >

The designer also refers to the behaviour knowledge base (see Figure 6.6), and the program will provide the following:

< #B01, Piezo-actuator, III, _, voltage, deformation >

It is noted that the retrieval of the effect and the behaviour may be automated, i.e., the program automatically searches the effect and behaviour knowledge bases with the id (#E01) and the id (#B01) respectively, and displays #E01 and #B01. Again, this is the matter of the computer implementation.

It is also possible that there are more than one effect and behaviour that could fulfil the function (#F01), i.e., in the FEBPSS 0A knowledge base, we may have the following two additional instances:

< #FEB01, Actuation, 0A, FEBPSS, #F01, #E02, #B02 >

< #FEB01, Actuation, 0A, FEBPSS, #F01, #E02, #B02 >

Therefore, there will be three possible effects and behaviours retrieved from the search for the solution to the function ‘high-momentum-motion.’ In this case, the designer will be provided with the following effects and behaviours:

< #E01, Piezo-electric effect, I, Physical effect (#PH02), description >

< #E02, electrostatic effect, I, Physical effect (#PH02), description >

< #E03, thermal-deformation effect, I, Physical effect (#PH02), description >

< #B01, Piezo-actuator, III, _, voltage, deformation >

< #B02, electrostatic-actuator, III, _, electric field, deformation >

< #B03, thermal-actuator, III, _, heat, deformation >

At this point, a choice has to be made among all these options. It is the designer’s discretion to make a final choice. To support the designer for this activity, the attribute in the effect and the behaviour knowledge base, called ‘description’, plays a role. In that attribute, some information that cannot be easily structured is stored to give basis for the design to make decisions. This information could be something as follows.

Both the electrostatic and the piezoelectric actuation principles provide very good reliability and energy efficiency. However, the electrostatic actuation can only give a very small displacement and the input and output relationship is non-linear; whereas the piezoelectric actuation provides a moderately generated pressure and displacement at the same time at simultaneously low power consumption. Also, it has high operation stability. Low power consumption results in low cost and high operation stability that contributes to the reliability of the system (one of the functional requirements of the system), and good pressure and displacement characteristics (note that all these facts are available in the knowledge base in the form of a template).

Hence, it is highly possible that after having read the above information under this description attribute, the designer chooses the piezoelectric actuation technique.

However, if none of the three fulfill the function properly, then a new actuation technique is searched but not from the current knowledge base. Assume that the new actuation technique is the shape memory alloy actuation technique (say). Then, this technique is transferred from the product-in-progress database to the design knowledge base and is stored there for future use. This way the knowledge base updates itself. The other very prominent example is the etching process. Suppose that to get a desired shape of the fluid chamber, a particular etching process is selected from the knowledge base. The (incomplete) device is sent for fabrication (i.e., etching in this case).

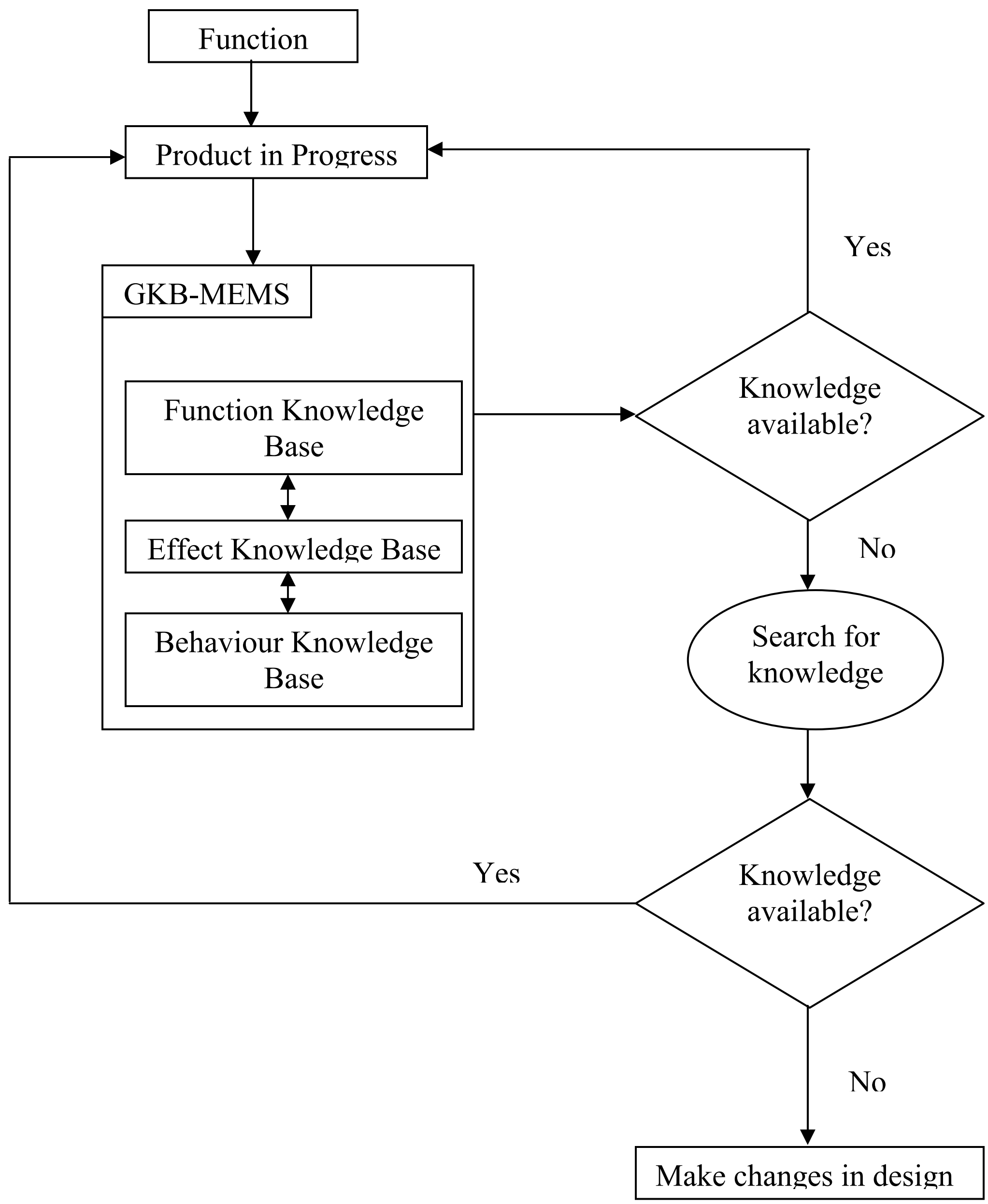


Figure 6.7: Dynamic updating of the knowledge base

If the selected etching process is not found efficient, then the other existing options are reviewed. If none of them is found suitable, then either a new etching process is searched or some changes are made in the existing etching process. This discussion above can be summarized in Figure 6.7.

6.5 Design Result Summary

In summary, the conceptual design of the microdispensing system is completed and is shown in Figure 6.8. The rationale behind the selection of the structure based on the functional requirements is explained in the following.

As explained in the previous section, the main functional requirements of the microdispensing system are: (1) to achieve high momentum motion for micro-litre fluid generation, (2) to have uniform flow rate; (3) to operate with high degree of reliability; and (4) to work in an environmentally friendly manner. The next step is to determine the structure that can fulfill the functions. This is done by taking the effects and the behaviours into account. To achieve the high momentum motion, some actuation mechanism is required. To achieve the actuation effect, various actuation techniques are compared, and the search is narrowed down to the piezoelectric actuation mechanism. Thus, the effect in this case is the piezoelectric effect. To realize the pressing of the fluid at a high rate, a membrane or disc is needed on which the piezoactuator can be mounted or glued. The related behaviour is the impact force by deformation of the membrane/disc on application of voltage to give the desired momentum; see Figure 6.8.

The second requirement of the system is a uniform flow rate. To achieve this function, a fluid chamber was designed from which the fluid is ejected (when impact force is applied) by controlling various flow parameters. The flow parameters in this case are viscosity, surface-tension, drive-pulse-amplitude, drive-pulse-shape, fluid-temperature, and internal-pressure. The shape of the fluid chamber is shown in Figure 6.8.

The next required function of the system is that it should be reliable over time. This is achieved by designing a system with high strength. The factors to be considered in this case are the selection of the structure that leads to minimum stress, friction, and bonding problems. Also, the shape of the nozzle is an important parameter to decide whether the device will work reliably or not. At the beginning, the shape of the nozzle was selected as rectangular. After fabrication, the rectangular shape was not found suitable in achieving the desired function. Therefore, the designer again searched the design knowledge database to select the other possible shape for the intended function. The final proven shape was circular.

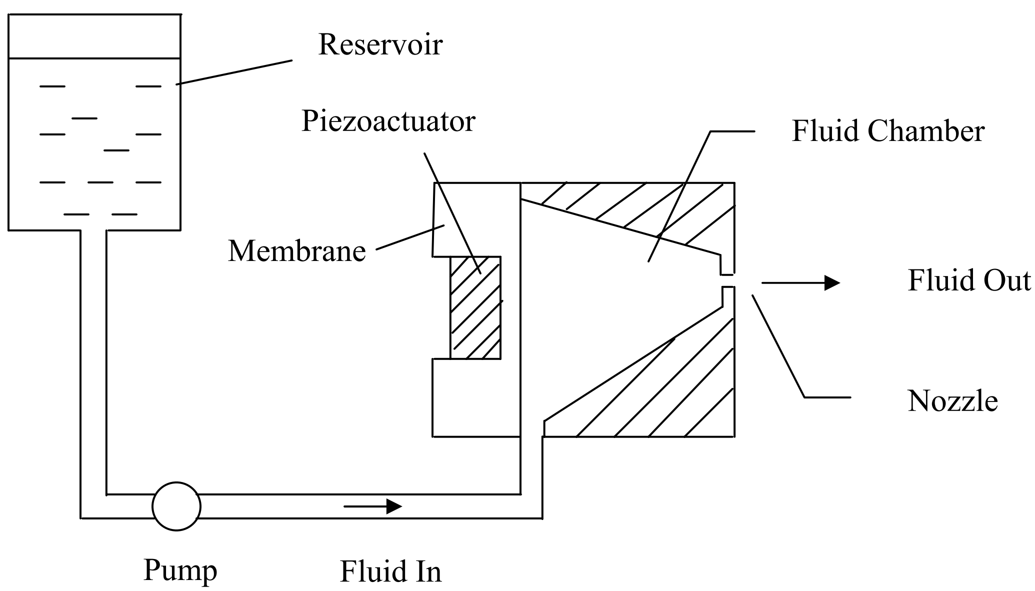


Figure 6.8: The conceptual structure of a microdispensing system

The last functional requirement of the dispensing system is that it should be environment friendly. To fulfill this function, the material of the dispenser must be compatible with the fluid to be used. The material should not produce harmful products when kept in contact with the fluid to be dispensed. Also, the material should not have adverse effect while fabricating. The intended behaviour is to use materials that are compatible with the fluid(s) to be used.

With regard to the constraint of small size, the selection of materials or components is on the basis of high functionality in low volume. So far as low cost of the system is concerned, the recommendation is to use cheap materials and processes (use wet etching in place of dry etching if both can achieve the same feature).

6.6 Conclusion

The case study has shown the effective procedure of the proposed GKB-MEMS approach. This approach has a feature of flexibility in creating knowledge and in updating knowledge. Therefore, the approach meets the requirements of MEMS product development in that changes occur rapidly both due to continuous updating and timely availability of microfabrication technologies. The example is about the conceptual design of a microdispensing system. The backbone knowledge base contains the function, effect, and behaviour concepts. When design moves on to the detailed design phase, the backbone structure (i.e., FEBPSS) contains the behaviour, principle, state, and the structure concepts. As such, the detailed information is determined; the calculation based on the principle/constraint equation can be performed to validate whether the desired states and behaviour are achievable. Therefore, this approach is of practical use for various design phases.

Chapter 7

Conclusions and Future Work

7.1 Summary of the Thesis

This thesis presented a study towards an effective computer support for MEMS products. A preliminary literature analysis began this thesis research. This analysis led to the main hypothesis underlying this thesis study, i.e., MEMS products involve high degree of uncertainty in fabrication, and the development process for them resembles the OKP product development process. To test this general hypothesis and develop computer based technologies for the MEMS product development, the following objectives were proposed:

Objective 1: *To analyze the MEMS product development process and to validate the statement that the contemporary computer aided design methods / tools are not suitable for MEMS product development, which further calls for a general approach to a new computer aided design method/tool for MEMS products.*

Objective 2: *To investigate the methodology for rapidly building or updating a design knowledge base for MEMS product development.*

Objective 3: *To analyze the computer aided design process management for MEMS products; in particular to identify unique features with the MEMS product development and to evaluate whether and how existing workflow management tools are applicable to MEMS product development process.*

A literature review was then conducted to confirm the statement in objective 1. An important phenomenon was observed that existing methods for building a knowledge base to support design are not unified and in addition, they appear rather rigid in terms of updating of a knowledge base. In Chapter 3, the characteristics of MEMS products and their development processes were further analyzed. This analysis justified the specific needs for research: (1) study of methods for building a flexible/general knowledge base, and (2) study of a computer based workflow management for the MEMS product development process. Subsequently in Chapter 4, the process for the OKP product development was closely examined. A comparison of the OKP product development and the MEMS product development was performed to justify why the tools for the OKP can be applied to the MEMS. Furthermore, further extension of these tools toward a more complete support for the MEMS product development was proposed.

In Chapter 5, a major effort was taken on to investigate a methodology for building a general and flexible knowledge base for MEMS. MEMS product development involves more changes than the conventional product development, and any knowledge base for MEMS product development is thus required to be able to adapt to the rate of technological change, especially referring to microfabrication technologies. The popular concept called the function-behaviour-structure (FBS) was extended and refined to be a backbone of a knowledge base for MEMS products. Furthermore, a template technique was formulated to achieve the goal of constructing a knowledge base by gathering several templates and updating the knowledge base by removing or adding new templates. The template technique proposed was inspired by the concept of reconfigurable systems through modularization.

Throughout the thesis, a design example of a microdispensing device was employed to illustrate the nature of MEMS product development and the type of knowledge bases needed to support MEMS product development.

7.2 Main Conclusions of the Thesis

(1) The MEMS product development process is of high uncertainty owing to its premature, non-standard, and expansive micro-fabrication processes. These features of the MEMS resemble the One-Kind-of-Production (OKP). As such, the MEMS

product development puts new requirements on computer support systems. The first new requirement is that a knowledge base for the MEMS should be flexible and general. The notions of the flexible and general together create a situation where a knowledge base can be updated easily and in real-time fashion.

(2) Existing computer aided methods and tools cannot be used to support MEMS product development because these methods do not provide a facility for formulation of a flexible and general knowledge base.

(3) Existing workflow management tools for the OKP can only meet the requirement of modifying the structure of a model (i.e., the Petri Net) but do not meet the requirement of decision making under uncertain and imprecise situation. These tools can be extended by applying the fuzzy and probabilistic theory to the Petri Net model with the varying structure feature.

(4) The function-behaviour-structure (FBS) framework appears to be a backbone for general/flexible knowledge base architecture. The extension/modification of the existing FBS framework, i.e., (a) the inclusion of concepts like principle and physical effect, and (b) the differentiation between structure and state, provide a complete FBS framework.

7.3 Contributions of the Thesis

The main contributions of this thesis are described below:

(1) **Characterization of the MEMS development process.** MEMS product development is of high uncertainty because of its premature, non-standard, and expansive microfabrication processes. The MEMS product development process is thus similar to the One-of-a-Kind Production (OKP) product development process.

(2) **Advancement of the function-behaviour-structure (FBS) framework.** Different studies on the FBS framework are compared in light of their similarities and differences. A more complete framework by including the concepts of the principle and the effect, and explicitly differentiating the structure and the state is proposed.

(3) **Development of a methodology for a general/flexible knowledge base for MEMS products.** The fundamental idea is to view a knowledge base as a modular system, which leads to the concept of modular knowledge base. The modular knowledge base has an inherent use, i.e., reconfigurable or adaptive knowledge base, which meets the requirements for MEMS product development very well.

(4) **Advancement of the computer aided workflow management tool for MEMS development.** Two basic requirements of any workflow management tool to support MEMS product development have been identified. One is that the model structure should possibly be changed dynamically, and the other is that decision making should possibly be made under the incomplete information situation. The current state-of-the-art of the tool is only a provision of the facility for the first requirement.

7.4 Future Work

This thesis study has a couple of limitations that warrant some further research. First of all, the idea of a flexible knowledge base through a template technique needs to be further elaborated; specifically the relationship of the template technique to the existing knowledge base tools needs to be understood. Second, the workflow management tool needs to be extended by providing the facility of decision making under the incomplete information situation in addition to the varying model structure property. Third, the work needs to be extended to include supply chain management under the virtual organization framework, as discussed that a sole owner of all microfabrication facilities may seldom be the case in practice. The development of a MEMS product requires effort from a group of companies.

References

Bracewell, R. and Sharp, J., 1994. "A computer aided methodology for the development of conceptual schemes for mixed energy-transforming and real-time information systems," in: Sharp, J. and Ho, V. (Eds.), *Computer Aided Conceptual Design,* LooseLeaf Co., U. K., 79-94.

Cao, L., Mantell, S., and Polla, D., 2001, *Design and Simulation of an Implantable Medical Drug Delivery System using Microelectromechanical Systems Technology*, Sensors and Actuators: A, 94 (1-2), 117-125.

Chang, E., Li, X., and Schmidt, L.C., 2000, *The Need for a Form, Function, and Behaviour-Based Representation System*, (http://www.enme.umd.edu/DATLab), 1-12.

Chen, X.B., 2002, *Modeling and Off-Line Control of Fluid Dispensing for Electronics Packaging*, PhD thesis, University of Saskatchewan.

Crary, S., and Zhang, Y., 1990, *CAEMEMS: An Integrated Computer Aided Engineering Workbench for Micro Electromechanical Systems*, Proceedings of IEEE Conference on Micro Electro Mechanical Systems (MEMS'90), Napa Valley, CA, 113-114.

De Kleer, J., 1984, *How Circuits Work*, Artificial Intelligence, 24(3), 205-280.

Desrochers, A.A., 1990, *Modeling and Control of Automated Manufacturing Systems*, IEEE Computer Society Press Tutorial: Washington.

Dixon, D., Kazalski, J., Murch, F., and Marongelli, S., 1997, *Practical Issues Concerning Dispensing Pump Technologies*, Circuits Assembly, 36-40.

Duribreux-Cocquebert, M., and Houriez, B., 1996, *User-centered methodology for knowledge based systems development: MODESTI*, Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, 2, 1208-1213.

Gero, J.S., 1990, *Design Prototypes: A Knowledge Representation Schema for Design*, AI Magazine, 11(4), 26-36.

Gero, J.S., Tham, K.W., and Lee, H.S., 1992, *Behavior: A Link Between Function and Structure in Design*, In D.C.Brown (ed.), Intelligent Computer Aided Design, North-Holland, Amsterdam, 193-220.

Gilbert, J.R., Ananthasuresh, G.K., and Senturia, S.D., 1996, *3D Modeling of Contact Problems and Hysteresis in Couple Electromechanics*, The 9th Annual International Workshop on Micro Electro Mechanical Systems, MEMS'96, San Diego, CA, USA, 127-132.

Guida, G., and Tasso, C., 1994, *Design and Development of Knowledge-Based Systems*, John Wley & Sons.

Gupta, S.M., and Moore, K.E., 1996, *Petri Net Models of Flexible and Automated Manufacturing Systems: A Survey*, International Journal of Production Research, 34(11), 3001-3035.

Highland, F., and Kornman, B., 1994, *Design Language and the Use of Cleanroom Methodology for Knowledge-Based System Development*, International Journal of Intelligent Systems, 9(9), 787-807.

Jensen, K., 1992, *Coloured Petri Nets: Basic Concepts, Analysis Methods and Practical Use*, Springer-Verlag.

Jinag, Z., Zuo, M.J., Fung, R.Y.K., and Tu, P.Y., 2001, *Coloured Petri Nets with Changeable Structures and Their Applications in Modeling One-of-a-Kind Production Systems*, Computers and Industrial Engineering, 41, 279-308.

Koltay, P., Steger, R., Birkle, G., Huang, H.C., Sandmaier, H., and Zengerle, 2001, *Microdispenser Array for Highly Parallel and Accurate Liquid Handling*, Presented at the SPIE's International Symposium MICRO/MEMS 2001, Adelaide, Australia.

Koppleman, G.M., 1989, *OYSTER: A 3D Structural Simulator for Micro Electromechanical Design*, Proceedings of IEEE Conference on Micro Electro Mechanical Systems (MEMS'89), Salt Lake City, UT, 88-93.

Korvink, J.G., Funk, J., Roos, M., Wachutka, G., and Baltes, H., 1994, *SESES: A Comprehensive MEMS Modeling System*, IEEE International Workshop on Micro Electro Mechanical Systems, MEMS'94, Osio, Japan, 22-27.

Lee, E.R., 2002, *Microdrop Generation*, CRC Press.

Lee, F.C., Mills, R.N., and Talke, F.E., 1984, *The Application of Drop-on-Demand Ink Jet Technology to Color Printing*, IBM Journal of Research Development, 28 (3), 307-313.

Madou, M., 1997, *Fundamentals of Microfabrication*, CRC Press.

Marteel, D., Menexiadis, D., and Soenen, R., 1993, *Maintenance knowledge base design methodology and building of an integrated preventive maintenance system (IPMAS)*, IFIP Transactions B: Computer Applications in Technology, B-11, 251-260.

Maseeh, F., 1990, *A CAD Architecture for Microelectromechanical Systems*, Proceedings of IEEE Conference on Micro Electro Mechanical Systems (MEMS'90), Napa Valley, CA, 44-49.

Maseeh, F., 1994, *A Novel Multidimensional Semiconductor Material Analysis Tool*, Solid State Technology, 37, 83-84.

Murata, T., 1989, *Petri Nets: Properties, Analysis and Applications*, Proceedings of the IEEE, 77(4), 541-580.

Nguyen, N.T., and Wereley, S.T., 2002, *Fundamentals and Applications of Microfluidics*, Artech House.

Pahl, G., and Beitz, W., 1998, *Engineering Design: A Systematic Approach*, Springer-Verlag.

Petri, C.A., 1962, *Kommunikation mit Automaten*, Ph.D. thesis, Bonn: Institut fur Instrumentelle mathematic. English translation: Holt, A.W., Communication with automata, Technical Report RADC-TR-65-377, 1966 1, suppl. 1 (New York: Griffiss Air Force Base).

Plant, R. T., and Tsoumpas, P., 1994, *Integrated methodology for knowledge-based system development*, Expert Systems with Applications, 7(2), 259-271.

Rai-Choudhury, P. (Ed.), 1997, *Handbook of microlithography, micromachining, and microfabrication*, SPIE Optical engineering Press.

Rodenacker, W., 1971, *Methodisches Konstruieren*, Springer, Berlin, Heidelberg, New York.

Rosenman, M.A., and Gero, J.S., 1998, *CAD Modelling in Multidisciplinary Design Domains*, In I. Smith (Ed.), Artificial Intelligence in Structural Engineering, Springer, Berlin, 335-347.

Scott, C.C., and Paksan, L., 2001a, *A Systematic Model for Redesign Using Function, Behaviour, and Structure to Facilitate Grammar Transformation*, eCAADe19*,* Architectural Information Management: Proceedings of the 19th Conference on Education in Computer Aided Architectural Design in Europe Ed H Penttilä (Otamedia Oy, Espoo, Finland) 18-24.

Scott, C.C., and Paksan, L., 2001b, *Describing Designs With Function-Behaviour-Structure Graphs*, The Proceedings of Mathematics & Design 2001 Ed M Burry, S Datta, A Dawson, J Rollo (Deakin University, Geelong, Australia) 74-81.

Senturia, S.D., and Howe, R.T., 1990, *Mechanical Properties and CAD*, Lecture Notes, MIT, Boston, MA.

Suh, N.P., 1990, *The Principles of Design*, New York: Oxford University Press.

Tseng, F.G., 2002, *Microdroplet Generators*, MEMS Handbook, Md. Gad-El-Hak (Ed.), CRC Press.

Umeda, Y., Takeda, H., Tomiyama, T., and Yoshioka, H., 1990, *Function, Behaviour, and Structure*, In Applications of Artificial Intelligence in Engineering, V, J.S. Gero (Ed.), Computational Mechanics Publications and Springer-Verlag, 177-193.

Umeda, Y., Ishii, M., Yoshioka, M., Shimomura, Y., and Tomiyama, T., 1996, *Supporting Conceptual Design Based on the Function-Behaviour-State Modeler*, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 10, 275-288.

van der Aalst, W.M.P., 1998, *The Application of Petri Nets to Workflow Management*, The Journal of Circuits, Systems, and Computers, 8(1), 21-66.

van der Wolf, P., 1993, *Architecture of an Open and Efficient CAD Framework*, Ph.D. Thesis, Technical University of Delft, The Netherlands.

van Stekelenborg, R.H.A., 1996, *On the Way to Supportive Information Technology for Contemporary Industrial Purchasing: A summary of four years of Dutch design-oriented research*, Heading for New Frontiers in Purchasing and Supply Management, Proceedings of the 5th International Annual IPSERA Conference, Eindhoven, NL, pp. 345-363.

Vishwandham, N., and Narahari, Y., 1992, *Performance modeling of automated manufacturing systems*, Prentice Hall, New Jersey.

Webster, 1998, *Webster's New World Dictionary of American English*, V.E. Neufeldt (Ed.), Webster's New World Dictionaries.

Wortmann, J.C., 1989, *Towards an Integrated Theory for Design, Production and Production Management of Complex, One-of-a-Kind Products in the Factory of the Future*, Proceedings of 6th Annual ESPIRIT Conference, Brussels, 1089-1099.

Wortman, J.C., 1991, *Towards One-of-a-Kind Production: The Future of European Industry*, Advances in Production Management Systems, Eero Eloranta (Ed.), Elsevier Science Publishers B.V. (North Holland), 41-49.

Zhang, W.J., 1994, *An Integrated Environment for CAD/CAM of Mechanical Systems*, Ph.D. Thesis, Technical University of Delft, The Netherlands.

Zhang, W.J., Crone H.A. and Werff van der K., 1994, *A software environment for integrated design and manufacturing of mechanisms: CIMOME*, In Advance of Computer-Aided Engineering, Delft University Press, The Netherlands: 81-88.

Zhang, W.J., and van Luttervelt, C.A., 1995, *On the support of computer-aided design process management: concept and implementation*, Annals of the CIRP, 44(1), 105-109.

Zhang W.J., 1996, *Methodology for Designing a Conceptual Database System to Support Partner Synthesis in Virtual Enterprises*, The Proceedings of the 3rd CIRP Workshop on Design and Implementation of Intelligent Manufacturing System (IMS), Tokyo, Japan, 137-144.

Zhang, W.J., Zhang D., and van der Werff, K., 1998, *An Integrated Data Model of Function, Behaviour, and Structure for Computer-Aided Conceptual Design of Mechanisms*, In Integrated Product and Process Development: Methodologies, Tools, and Technologies, J.M. Usher, U. Roy, and H.R. Parsaei (Eds.), John Wiley and Sons Inc., 85-124.

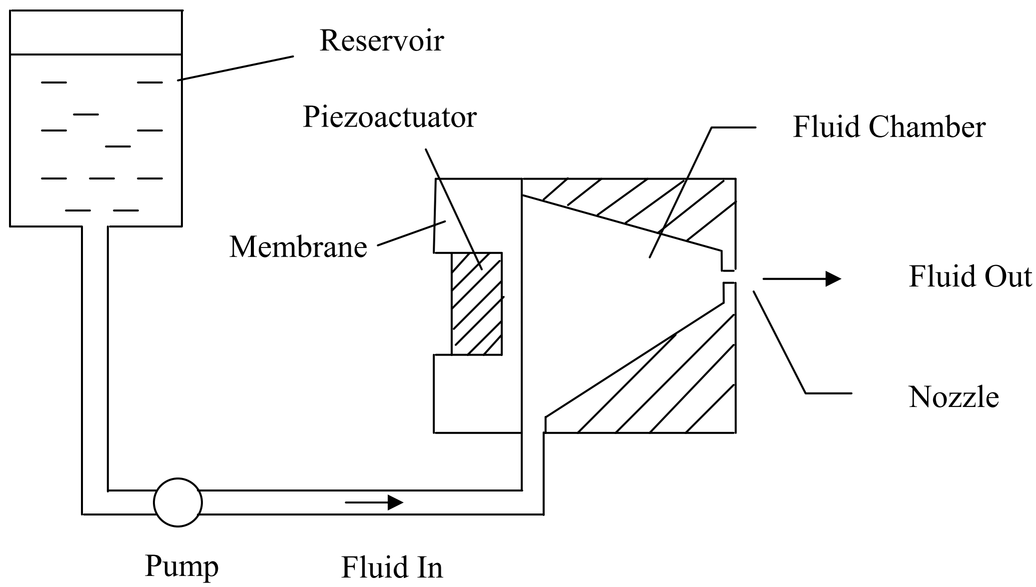
Zhang, W.J., 2001, *Lecture Notes on Advanced Engineering Design Methods*, University of Saskatchewan, Saskatoon, Canada.

Zhang, W.Y., Tor, S.B., and Britton, G.A., 2001, *A prototype knowledge-based system for conceptual synthesis of the design process*, International Journal of Advanced Manufacturing Technology, 17 (8), 549-557.

Zhao, W., El-Gizawy, A.S., and Billatos, S.B., 1996, *Knowledge-based system methodology for conceptual design of mechanical systems*, ASME, Design Engineering Division (Publication) DE, v 89, Design for Manufacturing and Assembly, 1-12.

Appendix A

Complete Microdispensing Device with Reservoir



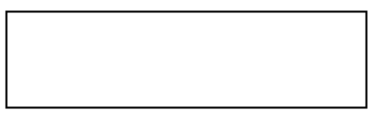
Appendix B

Fabrication of the Piezoelectric-Actuated Drop-on-Demand Dispensing System

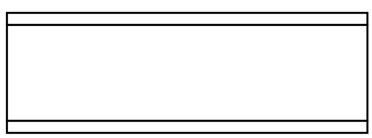
The fabrication of the piezoelectric-actuated drop-on-demand dispensing system proceeds in two parts. The two sections (membranes with actuator and chamber with nozzle) are fabricated separately and are joined at the end. In the following the fabrication processes used to get the desired feature are illustrated with the help of diagrams.

B.1 Fabrication Process of Membrane

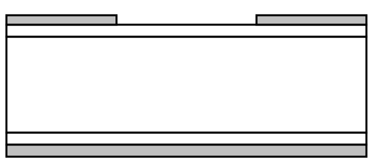
Clean the wafer



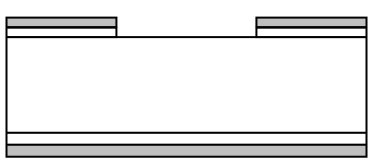
Coat the wafer with the masking layer



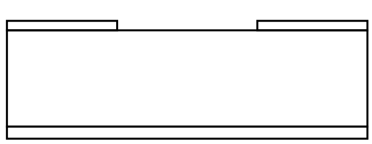
Apply photoresist on both the sides



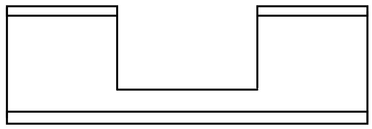
Etch away the masking part



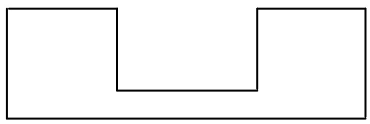
Strip resist



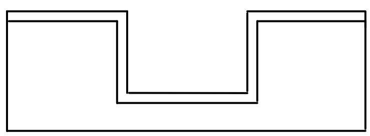
Perform etching to get the desired feature



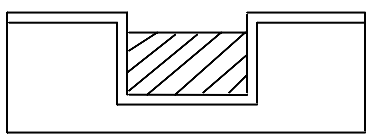
Strip the mask



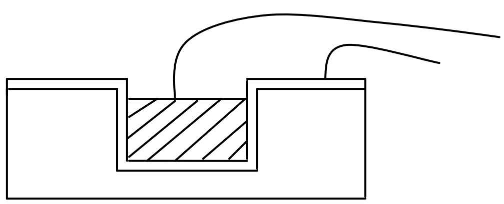
RF sputter thick titanium and thick gold that functions as a bonding pad



Manually glue the PZT actuator

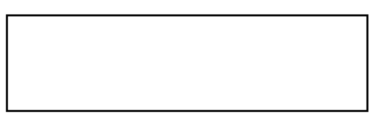


Manually glue the electrical wires on both the silver electrode on PZT actuator and gold layer

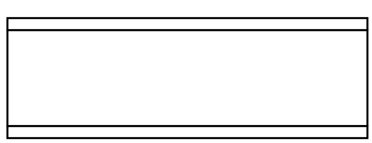


B.2 Fabrication Process for Chamber and Nozzle

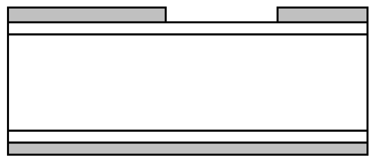
Clean the wafer



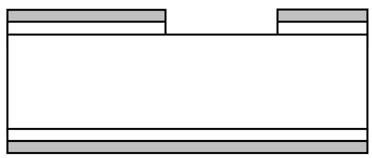
Coat the wafer with the masking layer



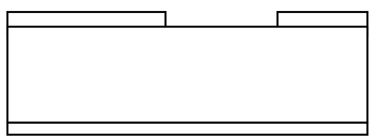
Apply photoresist on both the sides



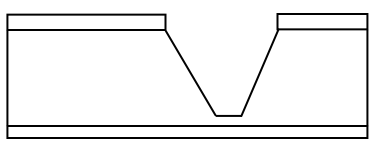
Etch away the masking part



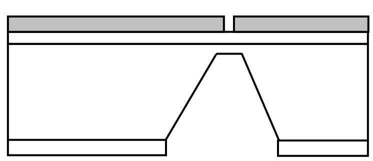
Strip resist



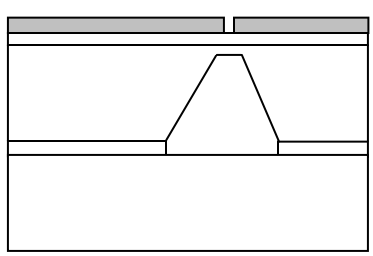
Perform anisotropic etching



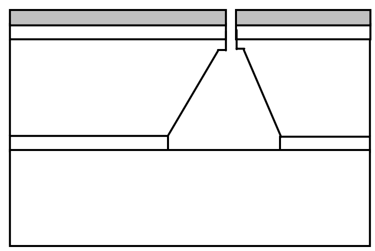
Apply photoresist on the backside and expose the nozzle part



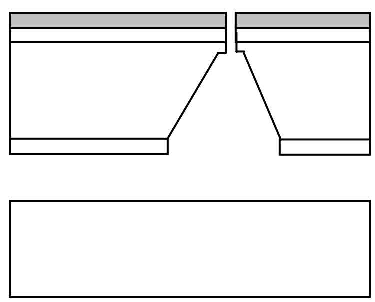
Glue wafer with photoresist to mounting wafer (to protect the wafer chuck)



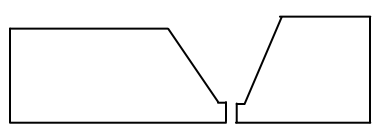
Etch ejection holes by etching



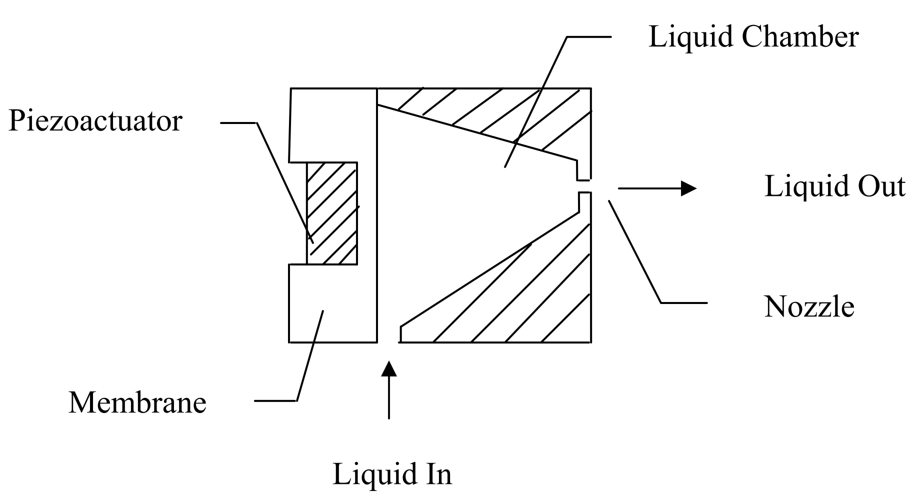
Debond the wafer



Etch the other side for making way for entrance for liquid



B.3 Join the two Wafers using Wafer Bonding Techniques



Appendix C

Petri Nets

Petri nets (PNs), first proposed in 1962 by Carl Adam Petri, are bipartite graphs and provide an elegant and mathematically rigorous modeling framework for discrete event dynamical systems.

Definition: A Petri net is a four-tuple (P, T, A, M) where

$P = \{p_1, p_2, p_3, \ldots, p_n\}$ is a set of places

$T = \{t_1, t_2, t_3, \ldots, t_n\}$ is a set of transitions

$P \cup T = \Phi$, $P \cap T = \Phi$

$A \subseteq \{TXP\} \cup \{PXT\}$ is a set of directed arcs

$M: P \longrightarrow I$ is a marking function, where $I = 0, 1, 2, \ldots\}$

M assigns *tokens* to each place in the net. A PN graph uses circles to represent *places* and bars to represent *transitions*. Tokens are represented by small black dots. Hence, token reside in places, travel along arcs, and their flow through the net is regulated by the transitions. When there is a token in each of the input places of a transition, that transition is enabled and fires. The transition fires by removing a token from each of its input places and by placing a token in each of its output places. This is referred to as the execution of a Petri net and it causes the marking to change, and therefore, token flow through the net [Desrochers, 1990]. This can be understood by the following Figure C.1.

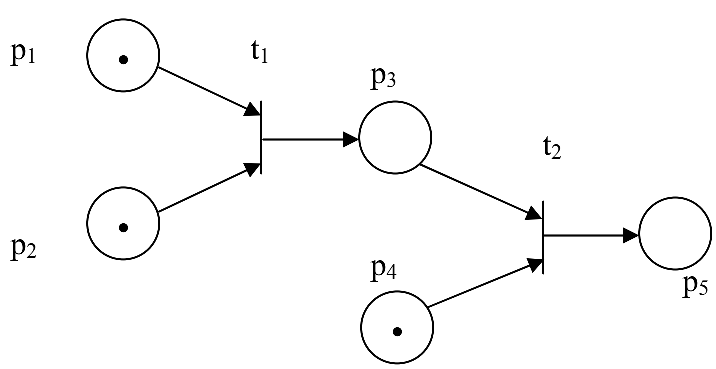


Figure C.1$_a$: Initial marking.

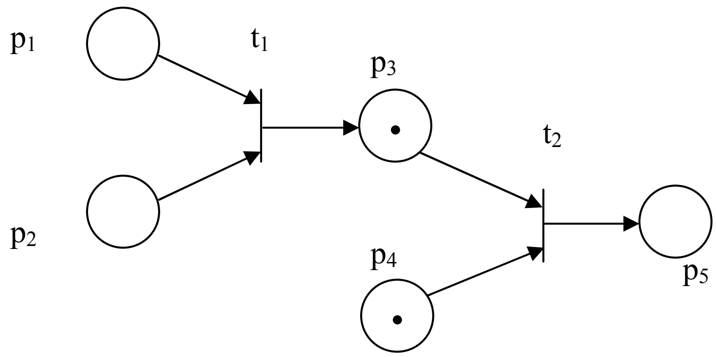


Figure C.1$_b$: Marking after t_1 fires.

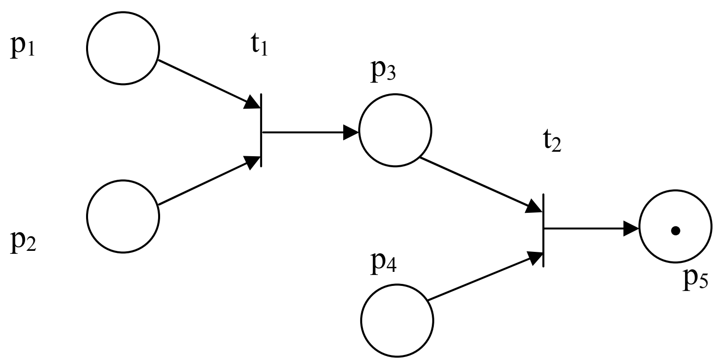


Figure C.1$_c$: Marking after t_2 fires.

Coloured Petri Nets (CPNs)

A CPN is defined as follows [Jensen, 1992]:

$$CPN = (\Sigma, P, T, A, N, C, G, E, I)$$

Where:

(i) Σ is a finite set of non-empty types, called colour sets.

(ii) P is a finite set of places.

(iii) T is a finite set of transitions.

(iv) A is a finite set of arcs such that:

$P \cap T = P \cap A = T \cap A = \Phi$

(v) N is a node function. It is defined from A into PXT U TXP.

(vi) C is a colour function. It is defined from P into ∑.

(vii) G is a guard function.

(viii) E is an arc expression function.

(ix) I is an initialization function. It is defined from P into closed expressions such that:

For all p Є P: [Type(I(p)) = $C(p)_{MS}$]

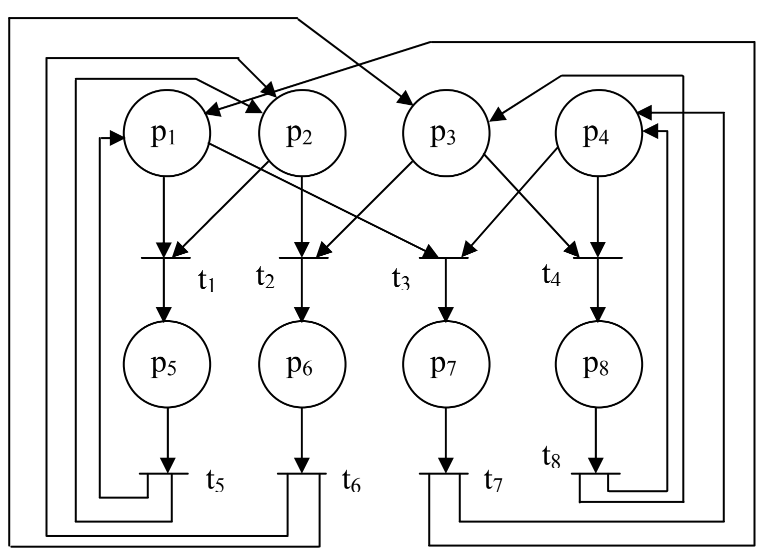
The places set P, the transition set T, the arc set A, and node function N determine the directed arc net graph that specifies static structure of a CPN model. Colour set ∑, guard function G, colour function C, and expression functions E specify the dynamic structure of a CPN. The initiation function I is used to generate the initial marking that represents the initial state of a system [Jiang et al., 2001].

Advantages of Coloured Petri Nets over Classical Petri Nets

This can be understood by the following example.

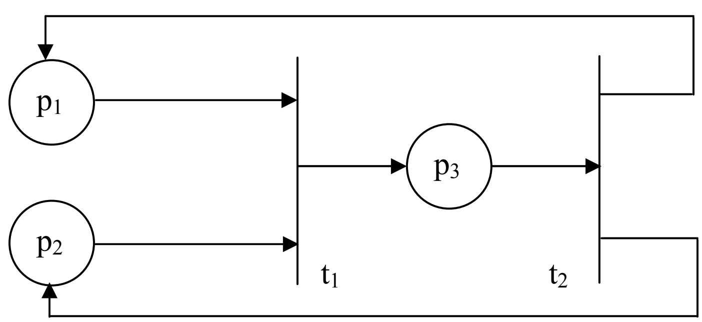
Example C.1:

There is a manufacturing system comprising two machines M_1 and M_2 and processing two different types of parts. Each part type goes through one stage of operation, which can be performed on either M_1 or M_2. On completion of processing of a part the part is unloaded from the system and a fresh part of the same type is loaded into the system.



p_1: Raw parts of type 1
p_2: Machine M_1 available
p_3: Raw parts of type 2
p_4: Machine M_2 available
p_5: M_1 processing a part of type 1
p_6: M_1 processing a part of type 2
p_7: M_2 processing a part of type 1
p_8: M_2 processing a part of type 2
t_1: M_1 starts processing a part of type 1
t_2: M_1 starts processing a part of type 2
t_3: M_2 starts processing a part of type 1
t_4: M_2 starts processing a part of type 2
t_5: M_1 starts processing a part of type 1
t_6: M_1 starts processing a part of type 2
t_7: M_2 starts processing a part of type 1
t_8: M_2 starts processing a part of type 2

Figure C.2: Classical Petri Net model of the given system.



p_1: Available fresh jobs (J1+J2)
p_2: Available machines (M1+M2)
p_3: Processing in progress
t_1: Transition indicating start of processing
t_2: Transition indicating finishing of processing

Figure C.3: Coloured Petri Net model of the given system.

Figures C.2 and C.3 show the classical and coloured PN models of the described manufacturing system [Viswandham and Narahari, 1992].

Appendix D

Definitions of Data Abstraction Notions [Zhang, 1994]

Definition D.1. The technique of emphasizing important issues while suppressing details is called *abstraction*.

Definition D.2. *Data Abstraction* can be defined as the process of organizing and refining the actual data values down to the important data values. The use of data abstraction produces systems that are usually smaller than the actual system. As a result, it is comparatively easy to verify the properties of the system at the abstract level.

Definition D.3. *Generalization* transforms the common properties or attributes of types of objects into a higher-level type of object (i.e., a generic type). The relationship between a generic type and its specialized type is sometimes called *is-a* link.

Definition D.4. *Specialization* is abstracting data in the opposite direction of the generalization.

Definition D.5. *Aggregation* transforms relationships among different types of objects into a higher level type of object. This relationship is sometimes called *has-a* link.

Definition D.6. *Decomposition* is abstracting data in the opposite direction of the aggregation.

Definition D.7. *Grouping* is based on the analysis of instances of one or more classes, and collects those instances together into a class whose instance values meet a defined criterion at the schema definition level as well as at the instantiation level. This relationship is sometimes called *member-of* link.