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INFORMATION AND KNOWLEDGE MODELING FOR COMPUTER SUPPORTED MICRO ELECTRO-MECHANICAL SYSTEMS DESIGN AND DEVELOPMENT

Xuan F. Zha[*], Ram D. Sriram
Manufacturing System Integration Division
National Institute of Standards and Technology
Gaithersburg, MD 20899

Satyandra K. Gupta
Department of Mechanical Engineering and Institute for Systems Research
University of Maryland, College Park, Md-20742

ABSTRACT

In this paper, we present a preliminary research effort towards an effective computer support environment for the design and development of micro-electro-mechanical systems (MEMS). We first identify the characteristics of MEMS product design and development processes and examine the state-of-the-art of MEMS Computer-aided Design (CAD) and simulation systems. We then propose a function-(environment-effect)-behavior-(principle-state)-form (FEEBPSF) framework based on the NIST core product model and its extensions for modeling MEMS products, and apply the OESM (open embedded system model) developed to model information and knowledge for embedded MEMS design and development. Moreover, in order to tackle the knowledge-intensive tasks of design and development for MEMS products, we develop a general and flexible knowledge repository, called KR-MEMS, based on the FEEBPSF framework and the Unified Modeling Language (UML)/ Extensible Markup Language (XML) model, and integrate KR-MEMS into a web-based MEMS design support system. Throughout the paper, a micro fluidic dispensing device (a biomedical device for drug-delivery) is used as an example to illustrate the concepts, models, and knowledge bases necessary to support the MEMS product design and development.

Keywords: Micro-electro-mechanical system (MEMS), computer support, information model, unified modeling language (UML), XML/XML schema, knowledge repository, collaborative framework, knowledge modeling

1. INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) are miniaturized devices with high functionality. Their sizes can range between a few dozen microns and a dozen millimeters. Often these MEMS devices are so small that it is nearly impossible to see them with the naked eye. In recent years, MEMS or MEMS embedded products (MEMS product for short in this paper) have become increasingly demanding in application. MEMS devices are widely used. Airbag sensors for cars and inkjet printers are two examples of application. Compared to macro-scale technology, MEMS technology is still in its infant stage and has several unique features. There are several challenges to be faced in MEMS technology. Because of their small size, MEMS require different design and manufacturing techniques than conventional devices. MEMS design and manufacturing knowledge is very complicated, thus it is very difficult to access. Computer technology that offers higher precision is an integral part in the design and manufacturing of MEMS. There are computer software packages available for the design and manufacturing of MEMS. However, MEMS design and development processes span multiple disciplines and involve a high degree of uncertainty, which calls for unconventional computer support to be effective. Further, a more comprehensive computer–based consultant system that includes thorough static and dynamic analysis for the design of MEMS is needed. As MEMS design and manufacturing knowledge is very specific and a knowledge-based system can assist human experts, design and manufacturing engineers should consult the knowledge-based system when designing and developing MEMS.

This research aims to develop a standards-based formal framework for modeling information and knowledge in MEMS product design, analysis and simulation. The work includes:

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[*] Corresponding author, Email: zha@cme.nist.gov

hardware/software co-design methodology; integrated framework for design, modeling & simulation, testing; and standard representation and protocols for exchanging and reusing system-level information and knowledge to enable design synthesis and semantic interoperability between design software systems in a virtual, distributed and collaborative environment through the entire life-cycle. A micro fluidic dispensing device or MEMS dispensing devices is used as a design example to validate the proposed approach and model.

The structure of the paper is as follows. Section 2 presents the current research status and review of computer-aided MEMS design. Sections 3 and 4 discuss modeling for MEMS product design and development processes, including UML and XML representations. Section 5 addresses the issues in building up a comprehensive knowledge repository for MEMS products, and provides a collaborative framework for MEMS virtual prototyping. Section 6 provides a case study of micro dispensing system. Section 7 summarizes the paper.

2. CURRENT RESEARCH STATUS AND REVIEW

2.1 Characteristics of MEMS Product Design and Development Processes

Before developing models for MEMS design and development, we need to investigate the characteristics of MEMS product design and development processes. The most important characteristic is the active reworking and the uncertainty associated with the design and microfabrication technologies and processes. The active reworking means that the reworking is defined in a process plan during the MEMS product fabrication progress. This can be attributed to (Niraj 2004): 1) very small size of the systems, 2) non-standardized microfabrication processes and rapid changes in the microfabrication technology, and 3) coupling of knowledge from different disciplines. For instance, LIGA (German acronym for LIthografie, Galvanoformung, Abformung) as a typical microfabrication technique integrates 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 very difficult. This is due to the fact that when a product is scaled for miniaturization parameters such as temperature and fluid properties affect the performance of the product to a much larger extent. In addition, the data/information about the micro properties and characteristics of most materials are still limited, and the selection of fabrication processes and materials for MEMS devices is still a difficult task (Zha and Du 2003). Another characteristic of MEMS product design and development processes is that a MEMS device frequently requires some chemical or biological substances to assist the fulfillment of its functions and performances. Therefore, the substances may become a part of the design solutions that designers need to explore during the design synthesis process. These substances may have physical interactions with the MEMS device; there may be certain chemical, biological or other reactions taking place between the substances, or between the substances and the MEMS device (Deng and Lu 2004). All these factors result in a very large design complexity and very long product development lead time for MEMS products.

2.2 Overview of MEMS CAD and Simulation Tools

There exist a number of commercial CAD systems developed to assist MEMS designers. Several worldwide projects are continuing to develop comprehensive MEMS design tools focusing on either device or system level CAD. They are derived either from existing microelectronic design tools or mechanical tools (Gilbert 1998). Such systems are at boundary between two large CAD industries: electronic design automation (EDA) and mechanical design automation (MDA). Thus, the major task of MEMS CAD systems is to intentionally integrate tools from MDA and EDA. Several vendors, including Coventor, ANSYS, ISE, and CFD Research Corp., are developing MEMS CAD software systems. Examples of MEMS CAD and simulation programs under development and developed so far are Oyster (Koppleman 1989), CAEMEMS (Grary and Zhang 1990), MIT's MEMCAD (now CoventorWare^{TM}) (Gilbert et al. 1993), IntelliSuite^{TM}, SESES (Korvink et al. 1994), IntelliCAD (Maseeh 1990), MEMSCAP^{TM}, An's MEMSCAD, Web-MEMS Designer (Zha and Du 2002, 2003), etc. Figure 1 gives an overview of existing MEMS CAD and simulation tools.

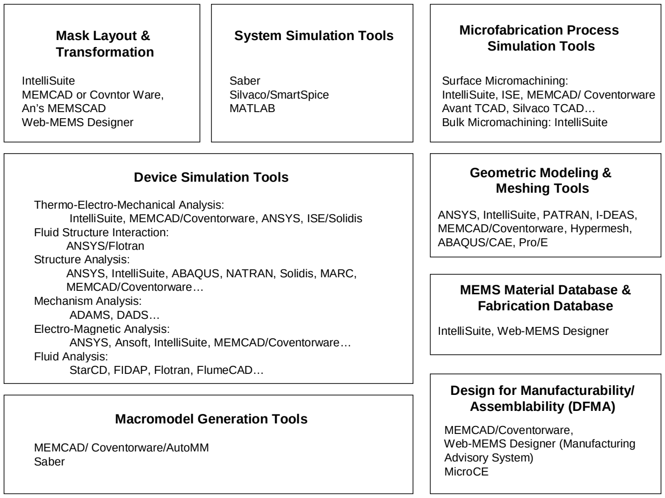


Figure 1: Overview of MEMS CAD and simulation tools

However, these tools focus on structure design of MEMS and limited support for design synthesis that links functions to structures (at the conceptual design stage). Moreover, these tools have not provided MEMS design process management and semantic interoperability between systems. To make a CAD system more flexible and interoperable, a comprehensive knowledge base/database is required, with a formal, systematic representation with less data and more semantic information/knowledge that keeps updating itself as the new information/knowledge arrives. The development of intelligent computer support systems for MEMS product design and development has become a highly demanding subject. One of the key technologies is to model artifact related functions, behaviors and forms (structures) in the lifecycle. The notable modeling approach for this is the widely accepted function-behavior-structure (form) (FBS) framework.

3. MODELING FOR MEMS DESIGN AND DEVELOPMENT PROCESS

3.1 MEMS Product Design Modelling Principle

Design modeling of MEMS is commonly divided into the following four levels: 1) system (e.g., airbag deployment trigger), 2) device (e.g., accelerometer), 3) component (e.g., springs), and 4) elements (e,g., rectangular cells on the mask). To model for the design and development of MEMS product and stick with the above four levels, the modeling approach adopted in this research identifies six abstraction levels: 1) enterprise, 2) system, 3) device, 4) component, 5) feature and 6) elements. The *enterprise level* modeling aims at providing a unified view of the system and its environment by capturing enterprise-related concepts. It may follow commonly used definition of the enterprise level modeling (this usually means modeling at the company level dealing with resource allocation and planning, forecasting, enterprise resource planning, etc.). The *system level* determines the system being developed, distinguishing it from its environment. The environment of a system consists of environmental elements, information systems or human users that make use of the services provided by the system itself, as well as other systems that provide some service used by the system being developed. The *component level* represents the system in terms of a set of composed components. A component may be further decomposed into sub-components. A composite component is an aggregate of sub-components that, from an external point of view, is similar to a single component. If a composite component is part of a component composition, the design process of this component corresponds to the design process of an isolated system, and the environment of this system contains the other components in the composition. The *feature level* defines the internal structure of simple components. A component is structured using a set of related features, which are implemented in a feature description and programming language. Thus, the development process of a component at the feature level corresponds to the feature-oriented development process similar to the traditional object-oriented process.

3.2 Core Product Model and Its Extension vs. FEEBPSF Framework

Currently, there exist several well-known design theories and methodologies developed for general (macro-scaled) systems, including: 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). Essentially, the design knowledge representation is based on the Function-Behavior-Structure (FBS) model (Chakrabarti and Bligh 1996, Cao et al. 2001, Gero 1990, Umeda et al. 1990, 1996, Sriram 2002, Zha and Du 2001).

The Core Product Model (CPM) is a knowledge-oriented product information model, developed at NIST to meet the requirements of anticipated next-generation CAD and product development systems (Fenves 2001, Fenves et al. 2005). It has been developed to unify and integrate product or assembly information. The CPM provides a base-level product model that is: not tied to any vendor software; open; non-proprietary; expandable; independent of any one product development process; capable of capturing the engineering context that is most commonly shared in product development activities. The core model focuses on artifact representation including function, form (structure), behavior, flow, material, physical and functional decompositions, and relationships among these concepts. The Entity-Relationship data model influences the model heavily; accordingly, it consists of two sets of classes, called object and relationship, equivalent to the UML class and association class, respectively.

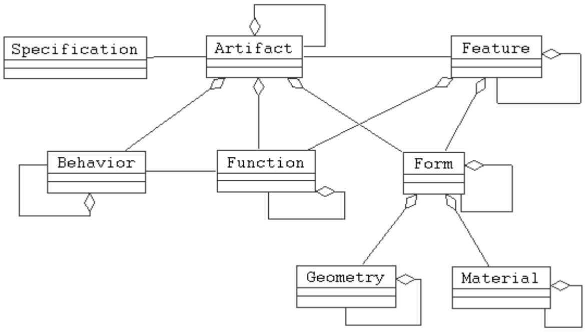


Figure 2: Entities in the NIST CPM Package

Figure 2 shows the principal entities in the CPM package. In the CPM, an **Artifact** refers to a product or one of its components, i.e, a product is represented by a hierarchy of entities of the class Artifact, which is an aggregation of **Function**, **Form** and **Behavior**. **Function** represents what the artifact is supposed to do; **Form** represents the proposed design solution (including structure of the product) for the design problem specified by the function; and **Behavior** represents how the artifact implements its function. Form itself is the aggregation of **Geometry**, the spatial description of the artifact, and **Material**, the internal composition of the artifact. Lower-level artifact entities may be labeled as **Features**. **Feature** represents any information in the **Artifact** that is an aggregation of **Function** and **Form**; purely geometric constructs are not treated as features in the CPM. In addition, an Artifact has attributes of **Specification** and **Feature**. Specification refers to the general information that contains all the design requirements pertaining to the artifact's function or form. All the above entities have their own independent containment ("part-of") hierarchies. The important relationships among entities are the **Requirement** relationship between the Artifact's **Specification** and some specified property of **Function** or **Form**, and the **Constraint** relationship on one or more such properties. The extension of CPM in the package consists of the **DesignRationale** class. For more information on the CPM, including the relationships (associations) defined between the classes shown; please refer to (Fenves 2001, Fenves et al. 2005).

In this work, we first extend the CPM to embedded systems, i.e., OESM (Zha and Sriram 2004, Zha, Fenves and Sriram 2005a,b) and then to embedded micro electro-mechanical systems (MEMS). Extensions of the CPM package involved expanding semantically the definitions of some concepts and/or extending existing classes or adding new classes. We intend to explicitly express concepts/entities such as working principle, state, effect, and working environment to facilitate the modeling of MEMS. The extended function-(environment-effect)-behavior-(principle-state)-form (FEEBPSF) framework has seven components.

(1) Function. The function of a system is defined as the purpose of the design and can be realized by the system form (structure) through the provision of certain behaviors by the form (structure). The function has two essences: (1) intentional and (2) extensional. The intentional part of the function is a total set of the 'intended' behaviors of the system. The extensional part of the function is the instances of the intentional 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 speed reducer is to "reduce the angular speed to 1:3"; the function of a nozzle is to "eject the liquid at a specified flow rate (say 4nL/s to 10nL/s)"; the function of the chamber is to "maintain the level of the fluid in the dosage chamber to a prescribed level" (Niraj 2004), etc.

(2) Environment. Any physical system has a surrounding environment. The environment consists of a number of environmental elements. Some environmental elements might have no interactions with the system, or do not affect the system's intended behavior, and are thus trivial to the design. The working environment includes only those environmental elements that contribute to the system's function and have attributes that affect the behavior of the system. Two kinds of relationship exist between the system and its environmental elements, i.e., a geometric relation and a physical interaction. The geometric relation characterizes the relationships between the system and its environment in the geometric aspect, namely, the spatial and assembly relation. The physical interaction refers to the situation where the source environmental elements provide input actions to the system, and the system provides output actions to the target environmental elements. These relationships might also have certain attributes. Thus, the working environment enables the functional output to achieve the functional requirement of behavior. Simply, the working environment includes those environmental elements of a system that contribute to the system's function or intended behavior (Deng et al. 2000). Recent work by Xu et al. (2005) discusses a formal modeling of use-environment.

(3) Effect. The effect is about the phenomenon that is observed (i.e., observed behavior). It embraces the rationale about how and why a particular behavior can be used for a functional purpose. The effect concept/entity stays between the function and the behavior to provide inference path from the behavior to the function.

(4) Behavior. The behavior of a system describes how the form of the system implements its function. The system behavior is governed by working principles which are incorporated into a behavioral or causal model. Application of the behavioral model to a system describes or simulates the system's observed behavior based on its form. The observed system behavior can then be examined with respect to the requirements to yield the evaluated behavior. Consequently, system behavior has three specialized attributes or slots to hold the system behavioral model, the observed system behavior and the evaluated system behavior (typically, URLs to the executable analysis program that embodies the behavioral model, the output of the behavioral model and the output of the external evaluation, respectively) (Fenves et al. 2005). Sometimes, the behavior of a system consists simply of the responses of the system when it receives stimuli and thus in this case the behavior takes the form of a set of transitions or changes of system states with respect to other states. The relationships among the state variables follow working (physical, chemical and/or biological) principles.

(5) Principle. The working 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, working principles are associated with the components, sub-systems, and systems as well. The principle concept/entity stays between the state and the behavior to give constraints such that given a set of (independent) state variables dependent state variables are found through the evaluation of the constraints.

(6) State. The state of a system is described by a set of entities, their attributes, and relations among them. The states of the entities are numerical or categorical quantities of physical, chemical or biological domains, for example, {0, 1}, {yes, no}, {open, close}, (- 0 +), $(-\infty\ 0\ \infty)$, etc. The states change with respect to time, constituting the dynamics of the underlying system. In order to systematically express the dynamics of the system, the states can be expressed by state variables. The states are related in various ways through the constraints imposed on the form (structure). These constraints come in two forms: external and internal.

Internal constraints are those related to the connection between entities that form the system at a time. External constraints are those imposed from the environment to the entities of the system. State variables can be further divided into independent and dependent state variables. For a particular system, its state variables and their dependencies are determined when the system is designed.

(7) **Form.** A system has a form (structure) that is a set of entities connected in a meaningful way. These entities are perceived through their states when the system is in operation.

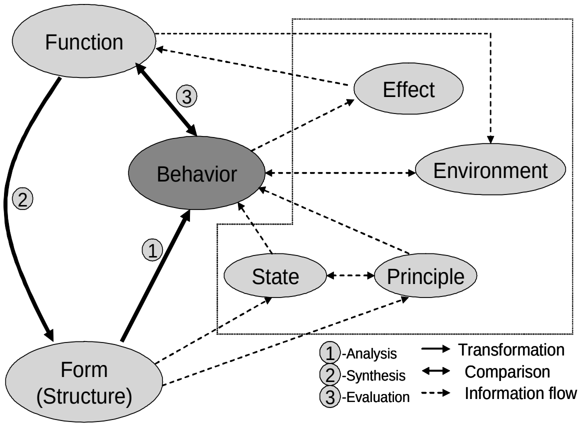


Figure 3: The FEEBPSF framework

Figure 3 depicts a general design template, called the FEEBPSF (F: function, E: effect, E: environment, B: behavior, P: principle, S: state, F: form) framework. Compared to frameworks for both macro and micro scale product modeling (Gero 1990, Umeda et al. 1990, 1996, Mukherjee and Fedder 1997, Niraj 2004, Deng and Lu 2004), there are a few distinct points in the FEEBPSF framework. First, the framework explicitly includes the environment, principle, state and effect concepts. Absence of these concepts in a knowledge representation will produce an incomplete knowledge base in the computer. In other words, knowledge of the environment, principle, state and effect has to be maintained. Second, the FEEBPSF framework explicitly distinguishes the form (structure) from the state, whereas others have only described them vaguely. When the behavior of a system is qualitatively evaluated, the state variable concept must be in a knowledge base.

3.3 Design-Analysis Integration Model

The CAD of a product's geometry and Computer-aided Engineering (CAE) for the analysis of its behavior are in common use today. Typically, a product's behavior needs to be analyzed in several functional domains (e. g., structural, thermal, kinetics, economics, etc.) and the results of the analyses may suggest design changes for improving or optimizing the behavior. The Design-Analysis Integration Model (DAIM) is a conceptual data architecture that provides the technical basis for tighter design-analysis integration than is possible with today's tools and information models. It is also intended to make analysis-driven design (often referred to as form-to-function reasoning) more practical. Eventually, it should also support opportunistic analysis, where the system tracks the geometric design process and notifies the designer when sufficient geometric information has been generated to initiate a functional analysis (Fenves et al. 2003). In this research, we intend to use DAIM for MEMS design-analysis integration.

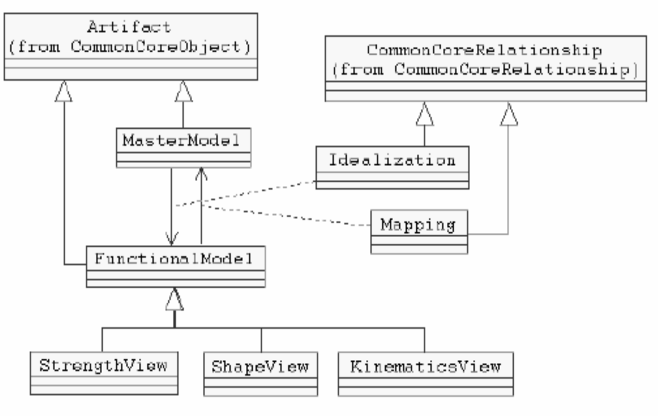


Figure 4: Design-Analysis Integration Model

The class diagram of the DAIM is shown in Figure 4. The **MasterModel** and the **FunctionalModel** are both specializations of the CPM **Artifact** class. The Master Model serves as the global repository of information on a product being designed; it may be implemented as a centralized distributed database, or virtual database. Each **FunctionalModel** represents an abstraction of the product of interest to a specific functional domain. The figure shows three representative specializations: a **StrengthView** for finite element modeling and analysis; a **ShapeView** for classical CAD geometry modeling; and a **KinematicsView** for kinematic modeling and analysis. The two models are linked by two association classes. **Idealization** is the transformation that creates a functional model specific to a particular domain from the master model; this is typically an abstraction operation removing detail irrelevant to the particular function, but more general transformations may also be used. **Mapping** is the reverse transformation of updating the master model based on changes in the domain-specific functional model; it is conceptually the more difficult transformation to define and implement, as it is responsible for maintaining full consistency between the two models.

3.4 Behavior-Driven MEMS Top-down Design Process

The design synthesis process starts from the function, via behaviors that implement the functions (i.e., behavior actors) and interact with the working environment (e.g., physical interactions, chemical/biological reactions), and results in the potential forms (structures). The potential forms (structures) are then evaluated and ranked to generate a best final solution. The transformation or mapping process is qualitative in nature.

There are two complementing approaches to supporting the top-down design process: function-driven and behavior-driven. The function-driven approach follows the traditional top-down design process (Pahl and Beitz 1998). The behavior-driven top-down design process adopts a component-based design approach. In this study, we propose a behavioral model enabled top-down design approach, which uses the generic behavioral reasoning for design synthesis. The traditional Function-Behavior-Structure (FBS) model regards a behavior as sequential transitions of states (Umeda et al. 1996). A library of features are used as building blocks, which consists of components and phenomena (behaviors, but effect in this paper) occurring on the components. These are represented by using the qualitative process theory (e.g., qualitative physics). A design synthesis can be achieved by combining such features according to working principles (physical laws). The FEEBPSF model in this research considers a behavior as the interactions between the components of the system as well as between the system and its working environment. A causal behavioral process, consisting of a network of causally connected individual behaviors delivered by each component or a set of components, is used to model the overall behavior of the system. Therefore, through the development of such a causal behavioral process, the design solution (form) can be identified.

As a result, a MEMS device/system can be designed using a library of behavioral model building blocks. MEMS component libraries include standard and optional parameterized MEMS libraries as well as mechanical and electrical components for use in creating MEMS schematic designs. These building blocks are feature-based parameterized in their forms (both geometry and material properties) and combined to produce the desired device behavior. The models are simulated in a circuit or network simulator to examine the device performance. Currently, electro-mechanical, optical, and fluidic behavioral models are provided for supporting MEMS top-down design in CoventorWare^{TM}. FEEBPSF framework is capable of supporting those models and integrating them.

Feature-based parameterized components increase modeling capabilities and ease of design. These components are composed of physical functions such as beams, plates, electrostatic gaps, comb drives, etc. that can be modeled analytically so that their behaviors can be governed by working principles or represented by mathematical functions. Complex systems, such as movable mirrors, accelerometers, gyroscopes, and switches can be modeled by combining these elementary components into a system model. The system model is typically captured in a schematic created in a schematic drawing tool. From the schematic, a netlist is extracted and simulations are performed using a network simulator. A system model typically has many fewer degrees of freedom than a Finite-Element Method (FEM)/Boundary-Element Method (BEM) model of the device, and therefore the behavioral simulations achieve accuracy comparable to FEM analysis but require much less computing time.

4. REPRESENTATION FOR MEMS MODEL

4.1 UML Representation for Embedded MEMS Model

Figure 5 shows the main schema of the Open MEMS Model (OMEMSM). The OMEMSM package is dependent on or instantiated from the OESM (open embedded system model (Zha and Sriram 2004, Zha, Fenves and Sriram 2005a,b) package. The model schema incorporates information about design specification, partitioning, MEMS specification, and component composition and configuration/assembly relationships. The model incorporates information about component composition (part-of) and assembly/ configuration relationship. The component composition of a MEMS is modeled using this part-of relationship.

A MEMS represented by the MEMS class is decomposed into hardware/software (HW/SW) subsystems and/or components, and connectors connecting these subsystems and components. Each MEMS component represented as **MEMSComponent** class in the **MEMSComponent** package, whether a HW/SW sub-system or component, is made up of one or more HW/SW features, represented in the model by **MEMSFeature** class in the **MEMSFeature** package. The class **MEMSComponent** represents MEMS component, which is a composition of **MEMSFunctionFeature**, **MEMSConceptFeature**, **MEMSParameterFeature**, and **MEMSStructuralFeature**. It is specialized into **HW_MEMSComponent** and **SW_MEMSComponent**. Components or subsystems in the embedded system are connected by connectors represented by **MEMS_Connector** class in the **MEMSConnector** package. Connectors may be either features or components or subsystems composed by features or components. The **MEMS** and **MEMSComponent** classes are subclasses of the **MEMSArtifact** class (extended from CPM Artifact class, see above). **MEMSFeature** is a subclass extended from the CPM **Feature** class. The composition (configuration/assembly) relationship is represented by a class named **CompositionAssociation**.

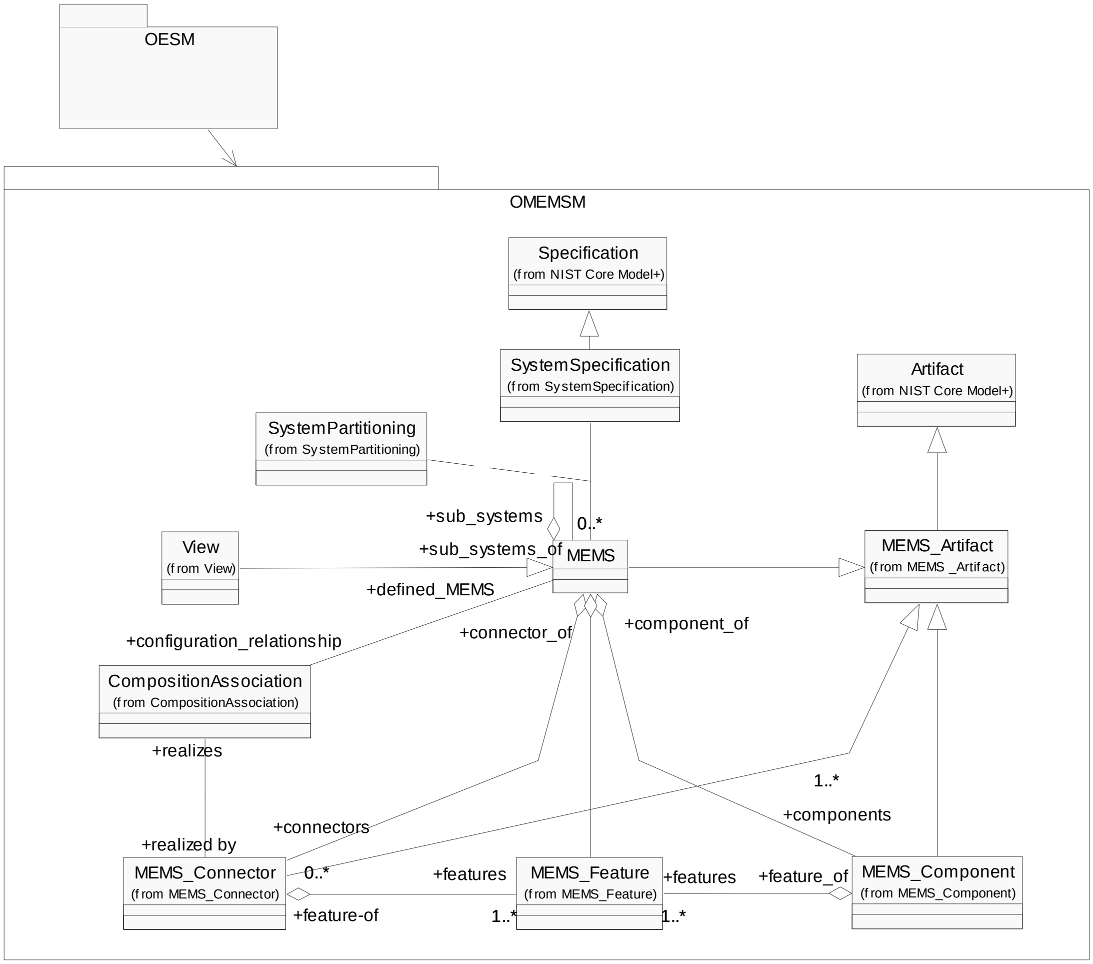


Figure 5: Main schema of the OMEMSM

4.2 XML Representation for Embedded MEMS Model

To advance the development of computer-aided design or virtual prototyping tools for MEMS, there is a need to address the formal representations of different abstractions of functional/ behavioral, structural, and product data along with their integration and exchange. Based on the formalism of unified component model and the taxonomy, we separate the information required for each standard/custom component into three distinct groups: functional/behavioral attributes, structural attributes, and parameter attributes. XML schema and XML are used for attribute-based feature representation in this research. The XML schema can be converted from the UML models.

5. KNOWLEDGE REPOSITORY FOR MEMS

Design process is a knowledge-intensive and collaborative task. Design knowledge should be structured for effective use (Szykman et al. 2001). A design knowledge base is a structured database of knowledge for concurrent design. Because MEMS products are designed and manufactured in a highly integrated manner, the design and manufacturing knowledge bases should be integrated into one as a development knowledge repository (KR-MEMS). To meet the demand of an effective computer support, there is a need to have a general and flexible knowledge repository for MEMS product design and development. In developing a generic knowledge-based system, two key methodologies can be used (Niraj 2004): framework technology and template technology. The framework technology is defined as a set of concepts or modules that are generic or common for more than one system component (van der Wolf 1993), which is thus to identify common building blocks (e.g., concepts, modules, etc.) for an underlying system. In a general system design, the examples of building blocks are the notions of function, environment, behavior, structure, and state, because every system shares these notions. The template technology is defined as a predefined pattern and it is instantiated when the pattern is put in use.

Specifically, KR-MEMS takes the FEEBPSF framework as a backbone (Figure 6) and is based on the UML/XML models built above. This backbone refers to individual knowledge bases for function, environment, effect, principle, behavior, state, and form (structure). Individual knowledge bases follow the XML schema (from the template technique) as discussed before. In some specific design situations (e.g., conceptual design), only solution principles are concerned; the FEEBPSF framework may only have the function, effect, and behavior concepts. The KR-MEMS is very flexible as it is easy to include or exclude an XML element (for a template) in KR-MEMS. For instance, if one wants to add a new effect (function, state, form,…) e.g., thermal-deformation effect into the KR-MEMS, one only needs to add an XML element representing the effect (function, state, form,…). It is further noted that the template technique is very similar to the modularization technique. Therefore, KR-MEMS offers a flexible architecture for knowledge base to fulfill the requirement for MEMS product design and development (Figure 7). Finally, the developed KR-MEMS (XML schema) is integrated into the web-based MEMS design support system (Zha and Du 2002, 2003) and used for design of micro fluid dispensing system.

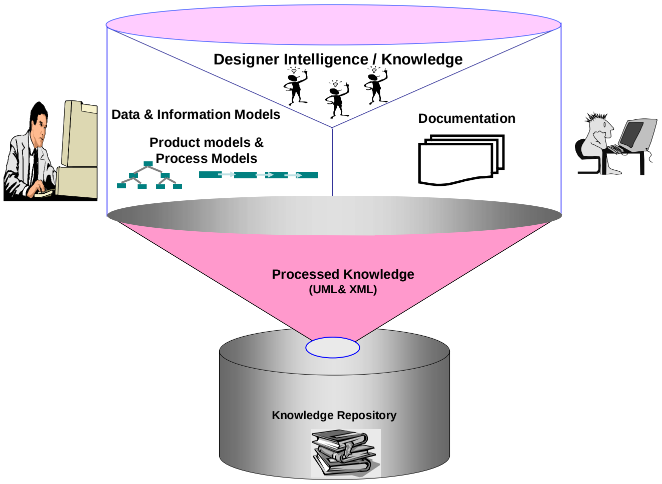


Figure 6: Knowledge repository for MEMS design and development

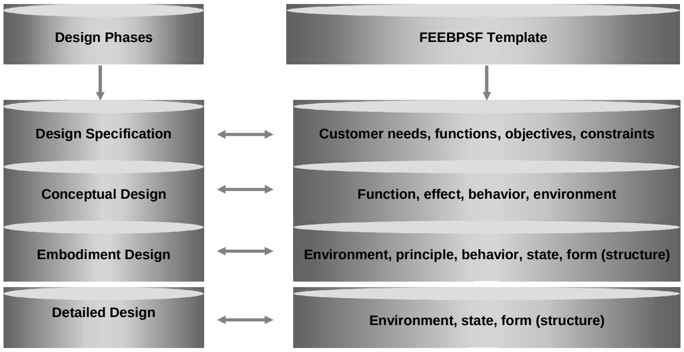


Figure 7: KR-MEMS and the design phases

Based on the information and knowledge models, we have proposed a multi-agent based virtual prototyping and design support framework for MEMS, as shown in Figure 8. The core of the scheme is the design knowledge management agent and knowledge repository, The design knowledge management agent and the knowledge repository are used to store, retrieve, share, and reuse the corporate design knowledge, as shown in Figure 6. The communication, negotiation and execution mechanisms between these agents can be modeled with the contract nets. To verify the proposed models and framework, the design synthesis agent, a subagent of design support agent, can be incorporated into the web-based MEMS design support system (Zha and Du 2002, 2003).

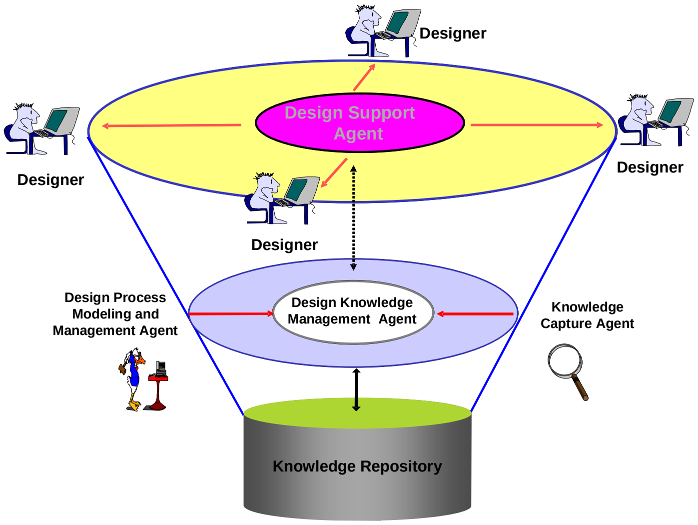


Figure 8: The overall collaborative framework for MEMS design support

6. CASE STUDY: A MICRO FLUIDIC DISPENSING DEVICE DESIGN

In this section, a micro fluidic dispensing device or MEMS dispensing devices is used as a design example to validate the proposed modeling framework.

6.1 Modeling for Micro Dispensing Device Design

The micro fluidic dispensing device has found wide applications in medicine, electronics, and chemical industries where the precise control of fluids is important (Tseng 2002, Nguyen and Wereley 2002, Niraj 2004, Ouellette 2003). For instance, in the cases of drug (medicine) delivery, fluid materials are delivered into the human body. The generic feature of the micro dispensing device 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. For the physical implementation of the relaxation and the refilling, an elastic membrane and a chamber need to be designed. A complete micro dispensing device is shown in Figure 9.

From the customer perspective, a list of requirements for this device can be described as follows: 1) efficient, i.e., dispensing an adjustable amount of small droplet fluids in a given time; 2) reliable over a long period of time; 3) uniform flow rate, especially for medical applications; 4) environment friendly; 5) as small as possible; and 6) low cost. From the engineering perspective, the above customer needs are converted into the following technical forms: fluid properties, viscosity, capillarity, drive pulse amplitude, drive pulse shape, internal pressure level, drop ejection rate, fluid temperature, material compatibility, and structure strength. The rationale of the selection for the structure is based on the following functional requirements: 1) high momentum motion for micro-liter fluid generation, 2) uniform flow rate; 3) high degree of reliability; and 4) environmentally friendly.

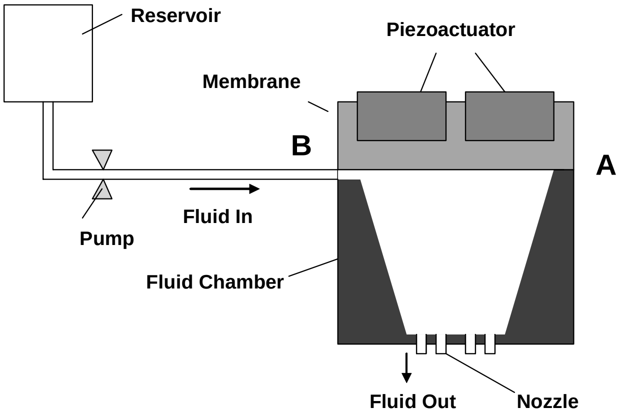


Figure 9: Micro fluid dispensing device

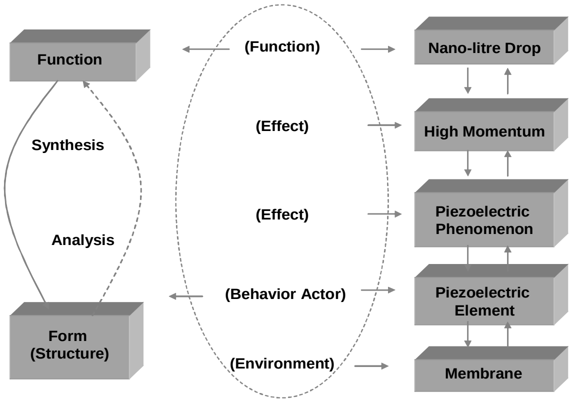
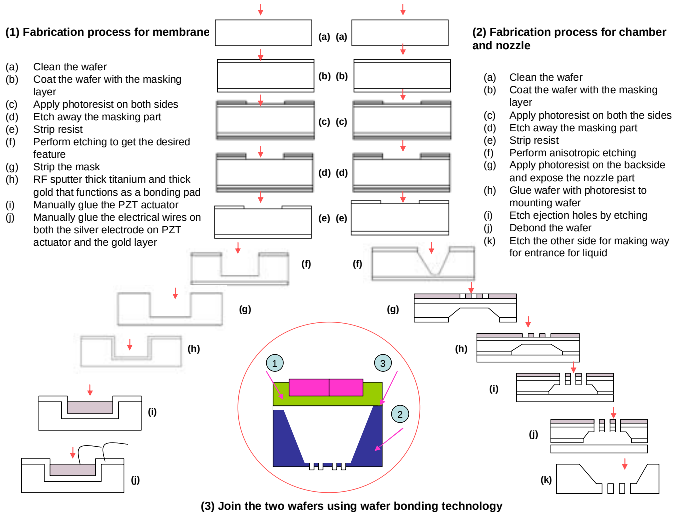


Figure 10: Role of the effect concept in micro dispensing device design

The next step is to determine the form (structure) that can fulfill the functions. It can be done by considering the effects and the behaviors. With regard to the constraint of small size, the selection of materials or components is based on the good functionality in a low volume. Considering the low cost of the system, the recommendation from the MEMS manufacturing advisory system (Zha and Du 2003) is to use cheap materials and processes, e.g., using wet etching in place of dry etching if both can achieve the same feature. The abovementioned (F, E, E, B, P, S, F) concepts/entities are related to each other, as shown in Figure 3. Table 1 provides an instantiation of the FEEBPSF framework in the micro fluidic dispensing device design. Figure 10 illustrates the role of the effect entity in design of the micro dispensing device. The effects (high momentum, piezoelectric phenomenon) provide an inference path from the behavior actor (piezoelectric element) to the function (nano-litre drop), interacting with the environment (membrane, cable). The fabrication of the piezoelectric-actuated drop-on-demand dispensing system can proceed in two parts (Niraj 2004). The two sections (membranes with actuator and chamber with nozzle) are fabricated separately and they are joined at the end. Figure 11 shows the proposed fabrication processes used to get the desired feature. As such, the fabrication knowledge can be elicited and incorporated into the knowledge repository.



(1) Fabrication process for membrane

(a) Clean the wafer
(b) Coat the wafer with the masking layer
(c) Apply photoresist on both sides
(d) Etch away the masking part
(e) Strip resist
(f) Perform etching to get the desired feature
(g) Strip the mask
(h) RF sputter thick titanium and thick gold that functions as a bonding pad
(i) Manually glue the PZT actuator
(j) Manually glue the electrical wires on both the silver electrode on PZT actuator and the gold layer

(2) Fabrication process for chamber and nozzle

(a) Clean the wafer
(b) Coat the wafer with the masking layer
(c) Apply photoresist on both the sides
(d) Etch away the masking part
(e) Strip resist
(f) Perform anisotropic etching
(g) Apply photoresist on the backside and expose the nozzle part
(h) Glue wafer with photoresist to mounting wafer
(i) Etch ejection holes by etching
(j) Debond the wafer
(k) Etch the other side for making way for entrance for liquid

(3) Join the two wafers using wafer bonding technology

Figure 11: Fabrication process of the piezoelectric-actuated drop-on-demand dispensing system

Table 1: Instantiation of the FEEBPSF framework in the micro fluidic dispensing device design

Function	The function of a nozzle is to "eject the liquid drop at a specified flow rate, say 4nL/s to 10nL/s"; the function of the chamber is to "maintain the level of the fluid in the dosage chamber to a prescribed level."
State and Form	The form of the system is shown in Figure 9. It has a structure which is a set of entities (membrane, fluid chamber, piezoactuator, nozzle, etc.) connected in a meaningful way. These entities are perceived in the form of their states when the system is in operation. The membrane must be in physical contact at the location A but not B with the chamber has implied that the constraint exists between the membrane and the chamber. 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. These state variables and their dependencies are determined when designing the micro dispensing system.
Behavior	The behavior of the nozzle can be stated as: given the flow rate at the inlet $9mm^3/s$ and the nozzle opening 20°, the flow rate at the outlet is found to be $4mm^3/s$.

Principle	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). The level of the fluid in the chamber 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.
Effect	The effect gives the rationale about why a particular behavior 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. A piezoelectric element serves as a behavior actor. 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.
Environment	The working environment enables the functional output (intended output) to achieve the functional requirement of behavior. For example, the environment output of the micro fluidic dispensing system is to provide the high-resolution fluid drops; the environment output of the piezoelectric element serves as a deformation to create high momentum based on the piezoelectric phenomenon. The working environmental elements of the piezoelectric element: membrane, and the cable for electricity.
Feature	We defined four categories of features in (Zha, Fenves and Sriram 2005): functional/behavioral features, structural features (form and interface features), parameter features, and concept feature. For a simple instance, the form feature of the piezoelectric element is cuboid; the parameter feature of the piezoelectric element is 3 dimensional parameters.

6.2 KR-MEMS for the Micro Dispensing System

The knowledge repository developed in this section is based on the XML schema and specialized for the micro dispensing system design. The design is restricted to the conceptual design phase. This implies that the FEEBPSF framework will contain only the artifact, function, effect, behavior and environment concepts. An XML element representing the micro dispensing system is provided below:

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<MEMSmodel xmlns="http://namespace.nist.gov/MEMS">
<artifact>
        <name>MicroDispensingSystem</name>
        <information>
              <description>
                 The System for dispensing fluids
              </description>
              <documentation>
                 This is a micro assembly with 6 different subartifacts
              </documentation>
              <fabricationProcessInformation>
                 The fabrication process for membrane
               </fabrocationProcessInformation>
        </information>
        <behavior>
             <theBehavior name="mdsBehavior"/>
        </behavior>
        <function>
             <theFunction name="generate micro-nano-litre fluid"/>
             <theFunction name="high-momentum-motion"/>
             <theFunction name="uniform-flow-rate"/>
             <theFunction name="high-reliability "/>
             <theFunction name="environment-friendly"/>
        </function>
        <forms>
      <theForm name="boxForm"/>
        </forms>
        <feature>
            <theFeature name="fluidInHole"/>
            <theFeature name="fluidOutHole"/>
        </feature>
        <effect>
             <theEffect name="piezo-electricEffect"/>
             <theEffect name="electrostaticEffect"/>
             <theEffect name="thermal-deformationEffect"/>
             <theEffect name="uniform-flowEffect"/>
        </effect>
        <environment>
            <theEnvironment name="membrane"/>
             <theEnvironment name="piezoelectrostaticElement"/>
        </environment>
….
        <subArtifact>
            <theArtifact name = "membrane"/>
            <theArtifact name = "pizeoactuator"/>
            <theArtifact name = "fluid chamber"/>
            <theArtifact name = "nozzle"/>
              …
             <theArtifact name = "reservoir"/>
         </subArtifact>
</artifact>
….
```

Figure 12 shows that the developed KR-MEMS is used for the design of a one-nozzle micro fluidic dispensing system in the web-based MEMS design support system.

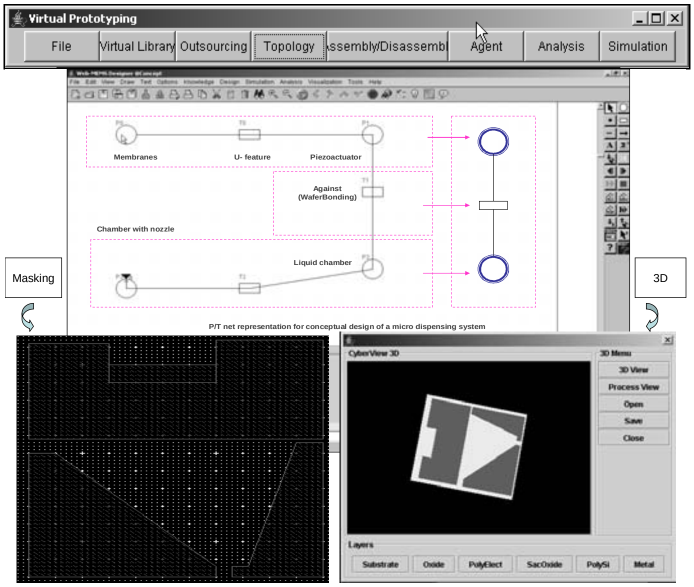


Figure 12: Virtual prototyping and design of a one-nozzle micro fluid dispensing device.

7. SUMMARY AND CONCLUSIONS

In this paper we presented an approach to modeling design and development processes of MEMS or MEMS embedded products. Based on the NIST core product model and its extensions in an FEEBPSF framework, information models were developed for MEMS product representation in a knowledge-intensive life-cycle support environment. A comprehensive knowledge repository was constructed for effective computer support to the design and manufacturing of MEMS or MEMS-embedded products in a fairly flexible and real-time manner. A micro dispensing device was employed as a design example to illustrate the concepts and models and the type of knowledge bases needed to support MEMS product design and development. Future work is expected in the following aspects: model improvement, FEEBPSF based design synthesis and system development, integrating the workflow management tool and the supply chain management tool under the virtual organization framework, etc.

DISCLAIMER

No approval or endorsement of any commercial product, service or company by the National Institute of Standards and Technology is intended or implied.

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