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Web-Enabled Knowledge-Intensive Support Framework for Collaborative Design of MEMS*

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ABSTRACT

Micro-Electro-Mechanical Systems (MEMS) design and manufacturing are inherently multi-physical and multi-disciplinary; no single person is able to perform a full development process for a MEM device or system. This chapter presents a web-enabled design platform for collaborative design of MEMS. The proposed web-based distributed object modeling and evaluation framework with client-knowledge server architecture, KS-DMME, allows multi-users/designers in different locations to participate in the same design process. Under this framework, concurrent integrated MEMS design and simulation models can be built using both local and distributed resources, and the design collaboration can be realized by exchanging services between modules based upon CORBA standard communication protocol. To facilitate the rapid construction of the concurrent integrated design models for MEMS, a prototype web-enabled design system, Web-MEMS Designer, is implemented through concurrent integration of multiple distributed and cooperative knowledge sources and software. By use of the developed prototype system, MEMS design and simulation can be carried out simultaneously and intelligently in an integrated but open design environment on the web. A case study of a microgripper design for micro robotic assembly systems is provided to illustrate how designers in different teams and organizations may participate and collaborate in MEMS design.

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Keywords: MEMS, World Wide Web, network-centric design, design with objects, distributed module modeling and evaluation (DMME), knowledge-based decision support systems, integrated design and analysis, collaborative design

1. INTRODUCTION

Micro-electrical Mechanical Systems (MEMS) are systems that generally incorporate silicon based electrical and mechanical elements at the micro level (10^{-6} m). It is estimated that the MEMS market has already reached around $30 billion. Micro-Electro-Mechanical Systems (MEMS) is a rapidly expanding field of multi-disciplinary technology, which takes advantage of semiconductor fabrication processes to produce micron-scale mechanical, fluidic, electric, optical, and other devices. MEMS devices are often integrated with microelectronic circuits, which control their behavior, perform signal processing and computing, and control/activate the behavior of the mechanical structures.

With the parallel development of new technologies, new device configurations, and new applications for microsensors, microactuators, and micro-systems, there has arisen a growing need for multi-disciplinary CAD support for MEMS. Needs, key issues and requirements in this arena have been identified, formulated, and reviewed in [39, 46, 47]. MEMS CAD shares some common techniques with the conventional CAD, but it is different in many ways. The multi-dimensional, multi-disciplinary, and multi-scale nature of MEMS makes the CAD software very difficult to develop [15]. Smart product design can be achieved with the aid of concurrent and intelligent concepts to facilitate design tasks. The inherently multi-physical and multi-disciplinary MEMS design problem requires new concurrent intelligent design methodologies and systems involving the integration of modeling, design, analysis and evaluation, and simulation for MEMS devices or systems as early as possible in the course of the different life-cycle phases. On the other hand, contemporary MEMS design problems often embody significant levels of complexities that make it unlikely that a single designer can work alone. The continuing growth of knowledge and supporting information and ever increasing complexity of design problems has led to increasing specialization. It has been recognized that further rapid progress in MEMS technology will be difficult to accomplish without a full range of multi-level hierarchical design tools (from a high-fidelity device level to a system level). Because of the heterogeneous structure of micro-systems, MEMS design and simulation requires different grades of abstraction and needs the cooperation/ collaboration of different disciplines and resources. Wide-area networks and the internet-based WWW allow users/designers to provide remote design servers. MEMS CAD systems running on these design servers can support a large-scale group of users/designers who communicate with the systems over the network. Based on the web protocols (e.g. HTTP), user/designer interfaces can provide access to the remote Web-based design servers with appropriate web browsers. Users do not need special hardware or software to consult these services. Thus, multiple users/designers in different locations are able to use the same CAD tool and design a MEMS device or system together. With the advent of Internet and WWW, it is expected that one of the focal research areas in MEMS design community will be on the development of web-based design framework/platform for collaborative MEMS design [43].

The purpose of this chapter is to present a web-based knowledge intensive development framework to facilitate the rapid construction of concurrent integrated distributed design models for MEMS, and to provide distributed designers with a platform/tool for collaboratively building these models. Specifically, in this chapter, the issues to be addressed include the following:

(1) To explore a new concurrent intelligent design methodology, involving the integration of modeling, design, analysis and evaluation, and simulation, for MEMS devices or systems;
(2) To develop a concurrent knowledge intensive design framework for MEMS design and simulation; and
(3) To develop a distributed intelligent platform for MEMS design and simulation using Java and CORBA over the web.

The structure of the chapter is as follows. It begins with an overview and requirements for network-centric design tools (Section 2). Then, in Sections 3 and 4, the web-based framework for supporting different types of collaborative design activities in a distributed design environment is developed for MEMS design, analysis and simulation. Section 5 provides a detailed implementation of the collaborative MEMS design system. A case study of collaborative microgripper design is provided in Section 6 to illustrate how designers in different teams and organizations may participate in the design of a microgripper for micro-robotic assembly system. Section 7 summarizes the chapter.

2. CURRENT STATUS OF RESEARCH

2.1. Computer-Aided MEMS Design

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. Software modeling tools are rapidly gained acceptance by the design community whenever /wherever they are applicable and useful. CAD tools permit the rational design of these devices and evaluate the effects of parameters such as temperature, strain, acceleration, etc. [32]. 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 1, with the design aids used to create the design, simulation to develop the technology, and verification to check the design. The final verification is to avoid wasteful and slow experiments by carrying out less costly computer work in order to get the fabrication right the first time [30].

Several CAD systems, which might facilitate the wider acceptance of MEMS, are discussed below. According to Senturia and Howe [45], the ideal suites of CAD tools required for MEMS development are [49]:

(1) Rapid construction and visualization of three-dimensional solid models;
(2) A comprehensive database of materials properties;

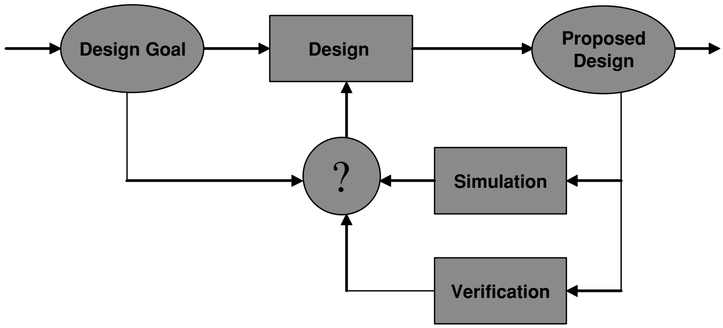

FIGURE 1. Design, simulation and verification in CAD systems

(3) Simulation tools for basic physical phenomena, e.g., thermal analysis, mechanical and structural analysis, electrostatic analysis, magneto static analysis, and fluid analysis;
(4) Coupled force simulators, e.g., thermally induced deformation, electrostatic and magnetostatic actuators, and interaction of fluids with deformable structures;
(5) Formulation and use of macromodels, e.g., lumped mechanical equivalents for complex structures, equivalent electric circuit of a resonant sensor, and feedback representation for coupled-force problems;
(6) Process simulation or process database, including, lithographic and etch process biases; and process tolerances on thicknesses, lateral dimensions, doping, and resistivity levels;
(7) Design optimization and sensitivity analysis, e.g., variation of device sizing to optimize performance, and analysis of effects of process tolerances;
(8) Mask layout;
(9) 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;

Several worldwide projects are continuing to develop comprehensive MEMS design tools focusing on either device or system level CAD. They are derived either from the existing microelectronic design tools (ECAD/TCAD) or mechanical tools [14]. 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 system. Some examples of MEMS CAD programs under development and developed so far are Oyster [24], CAEMEMS [7], MIT's MEMCAD (now CoventorWare) [13, 14], SESES [25], and IntelliSense [31], IntelliCAD, MEMSCAP, CyberCAD [57], An's MEMS CAD (2000), etc. Oyster facilitates the construction of a three-dimensional polyhedral-based solid mask set and gives a rudimentary process description. MEMCAD is directed at conceptual

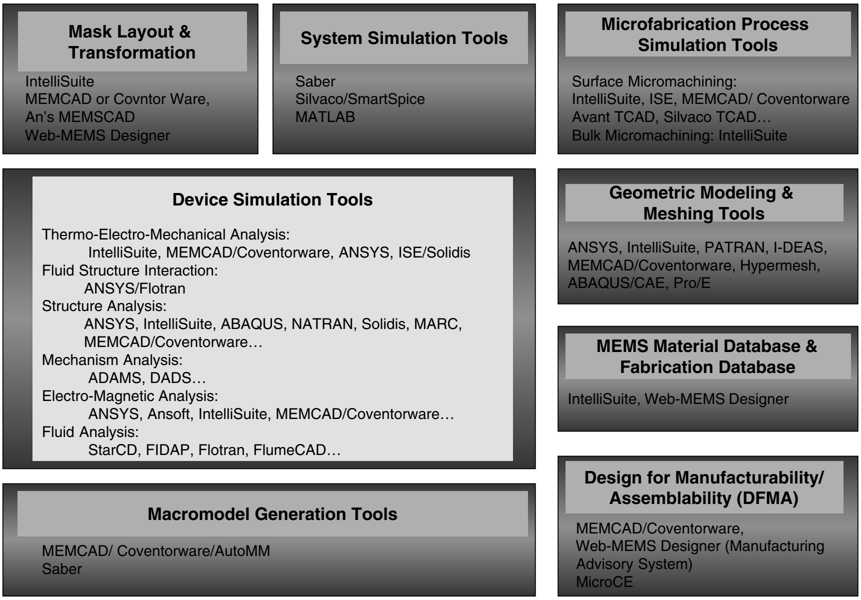

FIGURE 2. Overview of existing MEMS CAD and simulation tools

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. MEMS CAD is a free MEMS Layout Design tool under development with Java. Since it is programmed by Java, it works on all platforms, such as MS Windows, Linux, Sun, HP and SGI. Its basic functions are: 1) photo mask design, 2) mouse-driven drawing, 3) command-line free polyline drawing, 4) CIF data conversion with polyline, and 5) 3D exploded view with mouse/keyboard navigation. Figure 2 gives an overview of existing MEMS CAD and simulation tools.

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.

2.2. *Collaborative Design for MEMS*

There have been many research efforts on enabling technologies or infrastructure to assist product designers in the computer network-centric distributed design environment [11, 17, 28, 35, 36, 40, 50, 59, 64]. Some of them are intended to help designers to collaborate or coordinate by sharing product information and manufacturing services through formal or informal interactions [8, 26, 51]. Others propose formalized frameworks that manage conflicts between design constraints and assist designers in making decisions [8, 37, 38, 42]. There are also national-level efforts involving university and industry collaboration to make a variety of engineering services available over the Internet [29]. The RaDEO program is concerned with comprehensive information modeling and design tools needed to support the rapid design of electro-mechanical systems. It supports engineers by improving their ability to explore, generate, track, store, and analyze design alternatives.

The SHARE project by Toye et al [59] supports design teams by allowing them to gather, organize, re-access and communicate design information over computer networks to establish a shared understanding of the design and development process. While SHARE is primarily directed towards interaction through integrated multimedia communication and groupware tools, the NEXT-LINK project incorporates agents to coordinate design decisions affected by specifications and constraints [40]. A network-centric design system using interacting agents to integrate manufacturing services available over the network is under development [11].

The Electronic Design Notebook (EDN) is an interactive electronic document that maintains the look and feel of an engineering document to provide an integrated user interface for computer programs, design studies, planning documents, and databases [26]. Manufacturing tools and services are encapsulated in the hypertext documents and distributed through servers using HTTP [51].

A computer-based design system developed by Sriram et al [52, 53] provides a shared workspace where multiple designers work in separate engineering discipline. In their Distributed and Integrated Environment for Computer-aided Engineering (DICE) program, an object-oriented database management system with a global control mechanism is utilized to resolve coordination and communication problems. Design rationale provided during the product design process is also used for resolving design conflicts.

A design information system proposed by Bliznakov et al [5, 6] incorporates a hybrid model for the representation of design information at several levels of formalization and granularity. It is intended to allow designers in a large virtual organization to indicate the status of tasks assigned to each designer or team so that other designers can follow their progress. A central database manages pointers and access methods for product and process information in the distributed environment.

Hardwick and Spooner [17] propose an information infrastructure architecture that enhances collaboration between design and manufacturing firm. This architecture uses the WWW for information sharing and the STEP standard [33] for product modeling. It utilizes the CORBA standard for interoperability between software applications in the virtual enterprise.

N-dim is a computer-based collaborative design environment for capturing, organizing and sharing data [60]. It is a base, on which applications can be added for the purpose of history maintenance, access control and revision management. The primary focus of environment is on information modeling. The system provides a way for defining information types that capture the relations between data or models.

Pahng et al [35, 36] developed a Web-based framework for collaborative design modeling and decision support, based on the distributed object modeling and evaluation (DOME). The DOME framework asserts that multidisciplinary problems are decomposed into modular sub-problems. Modularity divides overall complexity and distributes knowledge and responsibility amongst designers. It also facilitates the reuse of modeling elements. Thus, DOME allows designers to define mathematical models or modules and integrate or interconnect them to form large system models. In DOME, a multiple attribute decision method is used to capture preferences and evaluate design alternatives from different viewpoints.

The above on-going research efforts pave the ways in which a network-centric design environment is able to support product designers and suggest what a computer-based design tool or system should look like in such an environment. However, they do not provide a structured and formalized framework for modeling the characteristics of multi-disciplinary and multi-objective design problems, and none of them are focused on the network-centric, distributed and collaborative design of MEMS. Existing CAD tools above for MEMS design, simulation and manufacturing are unable to support collaborative MEMS modeling and design activities. They are generally specialized and stand-alone applications. It is very difficult to use them for understanding and designing the integrated performance of product systems. Therefore, they are unable to support and coordinate highly distributed and decentralized MEMS modeling and design activities [72]. The motivation and vision presented in this chapter share some similar themes with [28, 35, 36] but emphasizes design and simulation modeling, decision-making, and search/optimization for MEMS.

3. KNOWLEDGE INTENSIVE COLLABORATIVE FRAMEWORK FOR NETWORK-CENTRIC DESIGN

Contemporary design process is knowledge-intensive and collaborative. The knowledge-intensive support become critical in the design process and has been recognized as a key solution towards future competitive advantages in product development. The integrated design requires the skills of many design designers and experts that each participant creates models and tools to provide information or simulation services to other participants given appropriate input information. It is the goal that the collective network of participants exchanging services forms a concurrent model of the integrated design.

Based on the DOME framework [35, 36], a web knowledge server framework, was developed for collaborative design process [66–69, 72]. The developed knowledge-intensive framework adopts the design-with-objects [66, 70], module network [4, 35, 36], and knowledge server paradigms [10]. The knowledge server paradigms are techniques by which knowledge-based systems can utilize the connectivity provided by the Internet to increase the size of the user base whilst minimizing distribution and maintenance overheads. The knowledge intensive system can then exploit the modularity of knowledge-based systems, in that the inference engine and knowledge bases are located on a server computer and the user interface is exported on demand to client computers via network connections. Thus, design

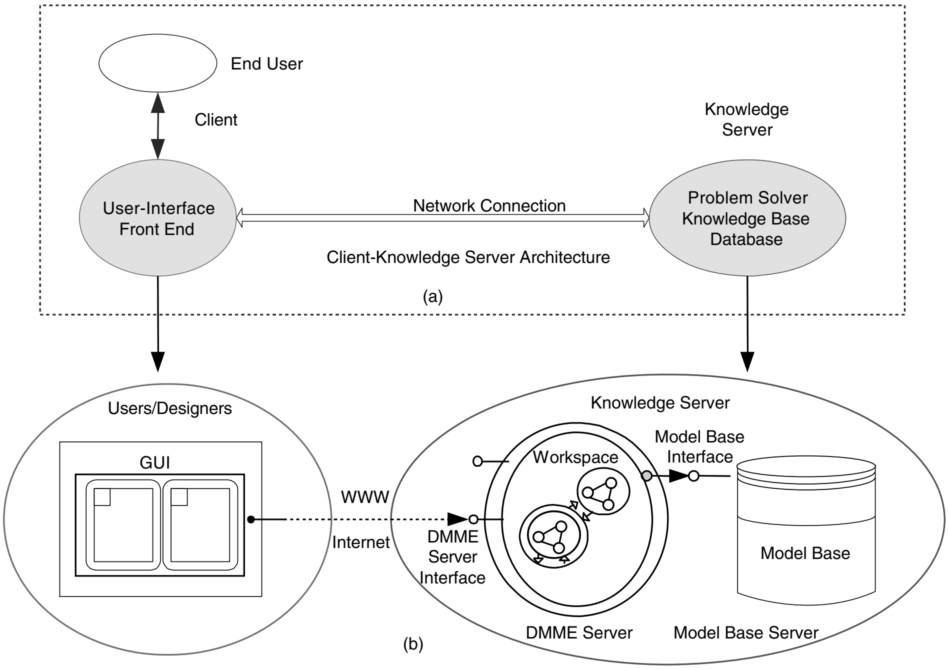

FIGURE 3. (a) Client-knowledge server architecture and (b) main components for KS-DMME

modules or objects are connected together so that they can exchange services to form large integrated system models. The module structure leads itself to a client (browser)/knowledge server-oriented architecture using distributed object technology. The main system components of the developed client/server architecture are shown in Figure 3. Each of these components interacts with one another using a communication protocol (CORBA) over the Internet so that it is not required to maintain the elements on a single machine. As a gateway for providing services, the interface of a system component invokes the necessary actions to provide requested services. To request a service, a system component must have an interface pointer to the desired interface.

With a client / knowledge server architecture, the characteristics of the knowledge intensive framework may be described as follows: (i) extensive knowledge based; (ii) hybrid intelligent system that integrates various knowledge sources; and (iii) concurrent, integrated, distributed. Thus, an intensive knowledge model for design is a large-scale knowledge framework that allows processing various types, different levels, and multiple functionality of knowledge in a design process [66].

4. KS-WebDMME FRAMEWORK FOR COLLABORATIVE DESIGN OF MEMS

The development process of MEMS devices or systems includes many steps from design, analysis and simulation, fabrication, to assembly/package and operation. Each of which is difficult, high-cost and time-consuming. Many loops of these steps are needed in the development process. In this section, we will discuss how the KS-WebDMME framework above is used for network-centric MEMS design, analysis and simulation process.

4.1. MEMS Design Process and Environment

A wide range of design problems are included in MEM devices or systems development, such as conceptual design, configuration design, process simulation, solid body geometric renderings from photo-masks and process descriptions, optimization of geometry and process sequence, micro assembly design, planning and simulation, and design of full systems. There are generally two rather different types of CAD requirements [47]: conceptual design phase and product-level phase. The first conceptual phase of a new device is to assist in finding practical configurations; the second product-level phase is to enable careful attention to physical behavior and parasitic phenomena. There is a great benefit if the actual device masks and process description can be used as input to the simulations. The rendering of three-dimensional solid models from mask and process data, both to permit checking of geometries and as input to physical simulation, assures that the device being simulated is also the one being built.

MEMS CAD can be categorized into the work at the following levels: system, device, physical/behavioral, and process level, in which lumped networks, energy-based macro-models, 3D simulation, and TCAD are included respectively ([47, 61, 62], MEMCAD 2000). The host of modeling and simulation requirements for a MEMS CAD system at these levels can be identified and described as follows:

(1) process modeling tools for all process steps;
(2) process optimization tools to achieve a desired device geometry (e.g., topology optimization);
(3) physical simulation in multiple coupled energy domain;
(4) construction of designer-useful behavioral models from simulation (micro models);
(5) device optimization tools to achieve desired device behavior;
(6) insertion of behavioral device models into system-level simulation tools;
(7) behavioral model optimization for desired system performance

In an ideal MEMS design environment, the user will first simulate the fabrication process steps to generate the 3D geometrical model including fabrication dependent material properties and initial conditions (e.g. fabrication induced stresses). The input to this simulation step is the mask layouts (e.g. in CIF or GDS II format) and a process description file (e.g. PFR). To compute fabrication dependent initial fields, the initial geometry model will be meshed and physics based process models (deposition, etching, milling, bonding, annealing, etc) will create a simulation-ready virtual model with complete definition of material properties, boundary and volume conditions, and physical/numerical parameters for field solvers. All model parameters should be specified directly "on geometry" rather than on mesh to allow multi resolution (grid independence) and solution-based mesh adaptation. The ultimate goal, of course, is that the device and the associated system are fabricated, and the system performance is as desired. To the extent that issues can be anticipated through simulation and modeling, also called computational prototyping, costly fabrication experiments can be reduced in number and increased in effectiveness. Figure 4 shows MEMS design methodology and modeling levels.

4.2. Web-Based Collaborative Design Platform for MEMS

Based on the design process of MEMS, the KS-DMME architecture for distributed collaborative MEMS design can be illustrated as shown in Figure 5. Under this framework,

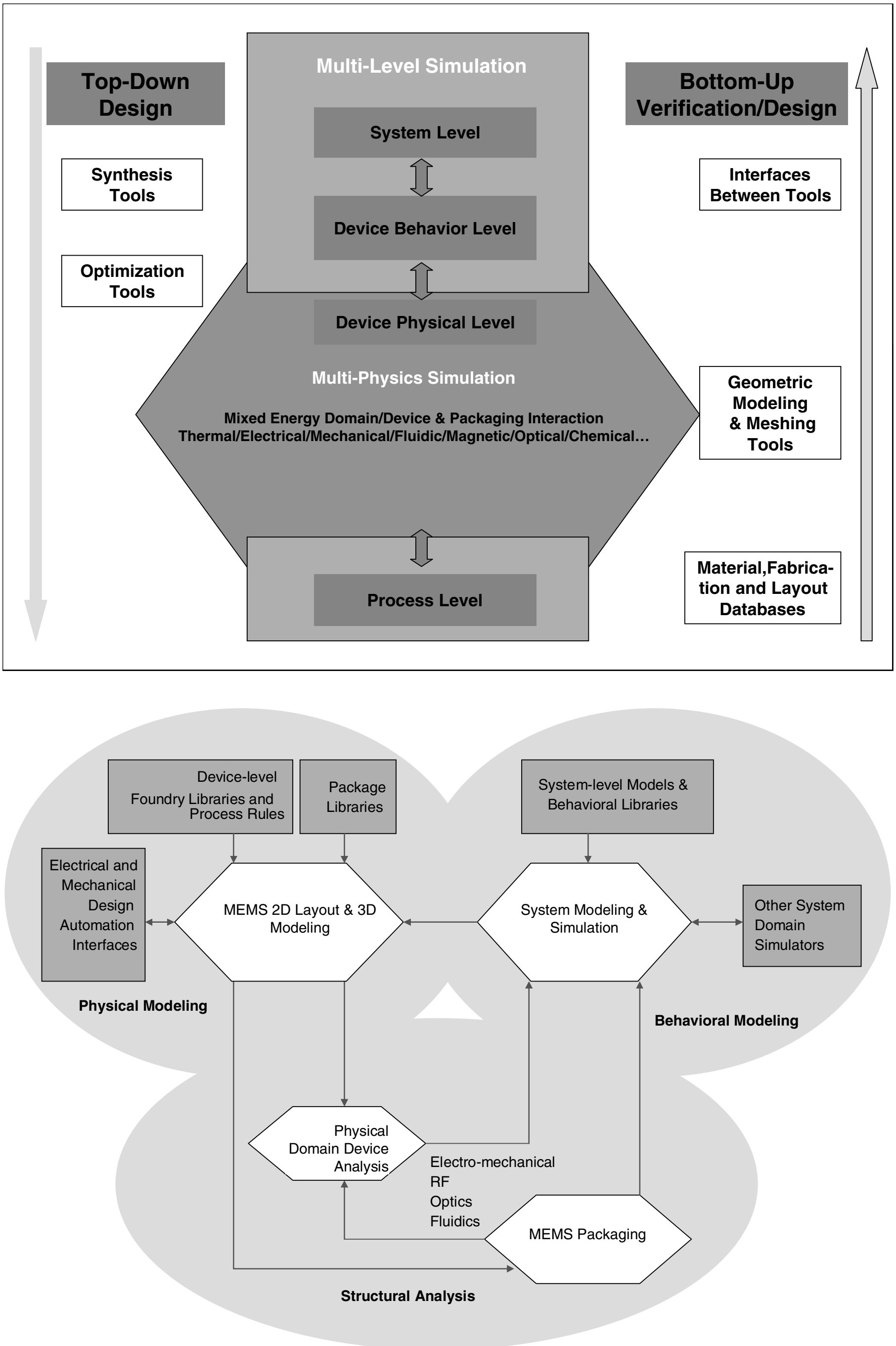

FIGURE 4. MEMS design methodology and modeling levels

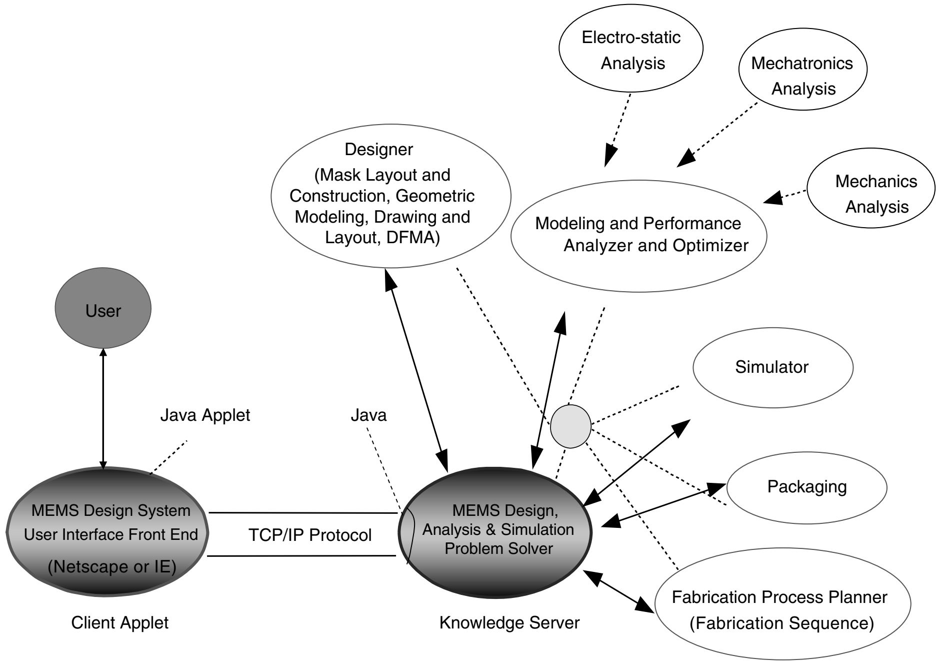

FIGURE 5. KS-DMME architecture for MEMS design, analysis and simulation

the requirements for the Web-based MEMS development tool can range from complex intelligent design, modeling, and simulation capabilities to more narrowly defined requirements. Its capabilities should be built into selectable or configurable, and knowledge-intensive modules that are packaged together to meet the requirements of a desired development flow.

The web-based collaborative MEMS design platform should be able to address the following issues: device layout and construction; device modeling and simulation; system modeling and simulation, and package, etc. The device layout and construction suite includes a direct, automatic connection between design of process and layout and full 3D-device modeling and visualization. It enables MEMS design to be driven by either experienced layout designers or mechanical engineers demanding full 3D editing capabilities. The device modeling and simulation suite provides solvers for the specific 3D physics of each kind of MEMS device. Specific knowledge on MEMS device modeling will be wrapped around state-of-the-art hybrid finite element and boundary element numerical tools. Thus, MEMS designers do not have to be experts in numerical techniques to get usable, accurate simulation results. The system modeling and simulation suite provides tools to help the designer understand manufacturing sensitivities and co-design of MEMS systems and devices. Design engineers can build and simulate accurate system models containing MEMS components integrated with external or on-chip circuit systems. Advanced tools enable automatic extraction of efficient, physically realistic SPICE and SPICE-like models of MEMS components from three-dimensional analysis. The packaging suite provides MEMS designers and packaging groups with tools to support communication and co-design. It enables true-coupled 3D package and device co-simulation. Package and MEMS groups can communicate by sharing quantitative models of package induced effects, along with tools to understand detailed device sensitivities to package design variables.

The solution to providing distributed MEMS design support in this research is to extend an original stand-alone MEMS design system, i.e., MEMS Designer [66], into a Web-based collaborative MEMS design system, i.e., Web-MEMS Designer. The system is deployed on a web server enabling access via the Internet a comprehensive suite of scalable and configurable software tools for MEMS design and simulation. Details about the implementation of the Web-based MEMS Designer system will be discussed below.

5. DEVELOPMENT OF WEB-BASED COLLABORATIVE MEMS DESIGN SYSTEM

To facilitate the rapid construction of the concurrent integrated models, a web-based collaborative design environment is essential for MEMS design and simulation. In this section, we describe the implementation of the prototype collaborative MEMS design system, Web-MEMS Designer. The focus is on the description of the technologies employed in the design and development of the Web-MEMS Designer system under the KS-DMME framework discussed above.

5.1. System Overview

The MEMS Designer system is a knowledge-driven design platform that delivers complete end-to-end development flow for MEMS-enabled devices or systems. It equips design engineers with the means to develop MEMS devices or systems from an initial concept through complete coupled analysis, which can also include package design characteristics, and ultimately extract high-level models for system simulation. The Web-MEMS Designer system exploits the modularity of knowledge-based systems, in that the inference engine and knowledge bases are located on server computers and the user interfaces are exported on demand to client computers via the Web. It is therefore a distributed intelligent development environment, consisting of 3D design, modeling and simulation software tools, which enable the creation of complex micro and/or MEM devices. The design flow of the MEMS Designer system is similar to MEMCAD that coordinates four key MEMS product development functions: layout and construction, device modeling, systems modeling and packaging analysis. The developed prototype MEMS Designer system contains a set of modules that are able to preliminarily support some of these functions, as follows:

(1) function-behavior-structure modeler for conceptual MEMS design (MEMS Designer @Concept) (Appdendix B);
(2) 2D drawing tool (including layout editor) (MEMS Designer @Concept);
(3) masking and fabrication process sequence builder (MEMS Designer @Builder);
(4) embedded manufacturing process and material databases (MEMS Designer @ Builder (MaskProcess));
(5) 3D geometric modeler and viewer (MEMS Designer @ Builder);
(6) manufacturing advisory system (MEMS Designer @ Advisor);
(7) embedded design optimization tool (e.g. GA tools) (MEMS Designer @Analysis);
(8) 2D and 3D FEM analysis (including an ANSYS interface) (MEMS Designer @Analysis).

The capabilities of these modules enable the MEMS Designer system to offer a special design platform for collaborative MEMS design, analysis and simulation.

5.2. System Implementation

The implementation of the prototype Web-MEMS Designer system is actually a three-stage process. The first stage was to convert MEMS Designer into a stand-alone application [66], involving the translation of the original knowledge base into an appropriate format and reconstructing the necessary functionality. The second stage was to convert the stand-alone application implemented in C/C++ into CGI executables that were deployed on a standard Web server, in terms of template Web pages to contain dynamically generated input forms, the necessary code to extract knowledge from submitted forms, and display results. The third stage was to implement the Web-MEMS Designer using Java and CORBA technologies integrating with a Java Expert System Shell, Jess/FuzzyJess, based upon Windows NT-based environment with a front-end Web-browser-based Graphical User Interface (GUI). Jess is a multi-paradigm programming language that provides support for rule-based, object-oriented, and procedural programming system language. The underlying modules are written in Java/Java3D/JDBC, respectively. The implementation architecture shown in Figure 6 uses the two-tier client/ knowledge server architecture (Figure 3) to support collaborative design interactions. Designers can integrate MEMS design problem models with the existing application packages, such as Java3D and JDBC for CAD and database applications.

The CORBA [48] standard is used to add distributed communications capabilities to modules (Orbix and OrbixWeb from IONA Technologies Ltd [20]). CORBA serves as an

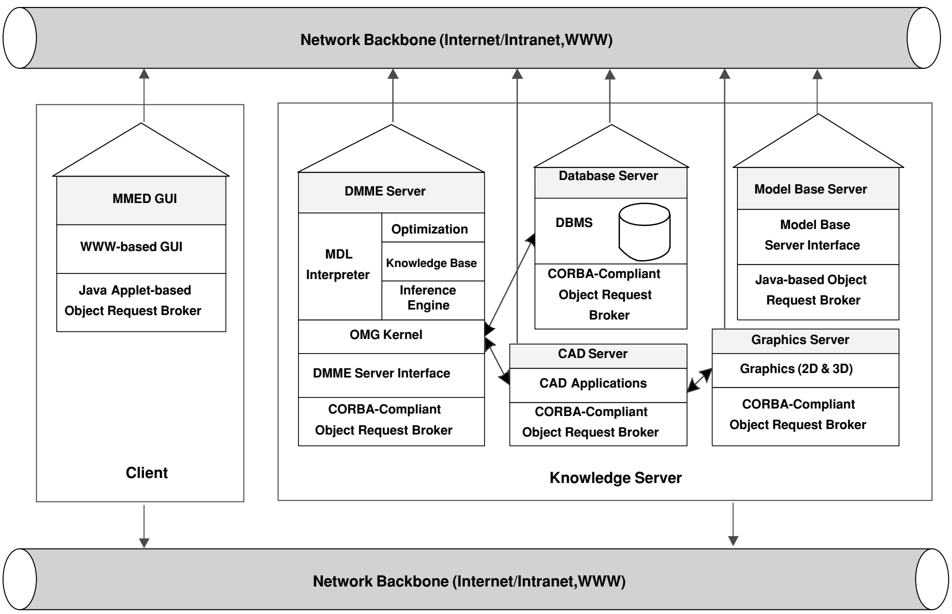

FIGURE 6. Implementation of the open design environment

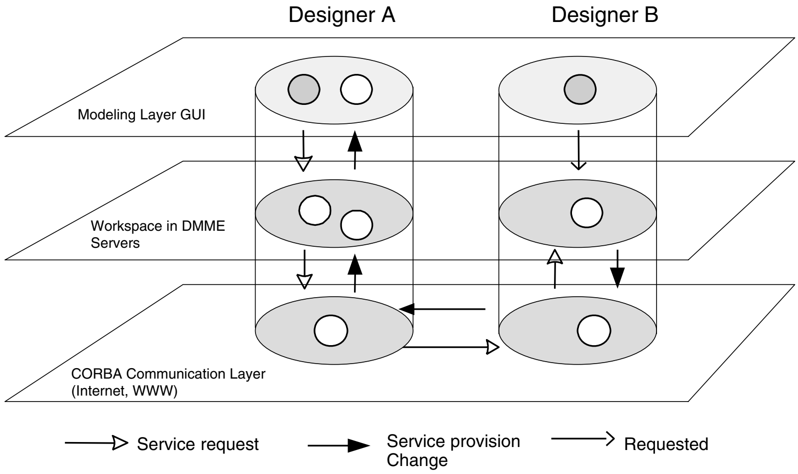

FIGURE 7. Service exchanges between distributed modules

information and service exchange infrastructure above the computer network layer and provides the capability to interact with existing CAD applications and database management systems through other Object Request Brokers (ORB). In turn, the KS-DMME framework provides the methods and interfaces needed for the interaction with other modules in the networked environment. These interactions are graphically depicted in Figure 7. When Designer B makes a change, the service corresponding to the request from Designer A will reflect the design change. The enumerated request shows the sequence for Designer A needs obtaining the service that. The light gray module seen by Designer A is the remote module published by Designer B. The underlying collaboration mechanism is based on the board systems. Each modular system has two-board systems, black and white board, as shown in Figure 8. The blackboard system is used for the local modular system to store intermediate reasoning and calculation results. It dynamically flushes in running. The whiteboard system is used for collaboration, which is actually a bulletin board system.

The Web-MEMS Designer GUI provides users with the ability to examine the configuration of design problem models, analyze tradeoffs by modifying design parameters within modules, and to search for alternatives using an optimization tool. The GUI is a pure client of the DMME server, delegating all events to an associated DMME server. For wide accessibility and interoperability, the GUI is implemented as a Web browser-based client application, which is a combination of HTML/XML documents and Java applets. For the CORBA-based remote communication between the GUI Java applets and the back-end side system components such as DMME server, CAD server, graphics server, and model base server, a commercial ORB implementation of Java applets (OrbixWeb) is employed [20]. Based on the system implementation architecture in Figure 6, the functionality of the knowledge server is achieved through implementing DMME servers, model base server, core knowledge engine, database server, and even knowledge base assistant and inter-server communications explanation facilities. Figure 9 shows several demonstration screenshots of

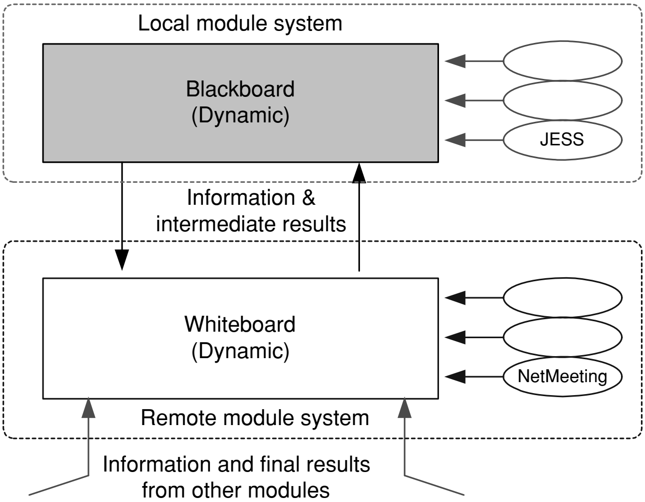

FIGURE 8. Blackboard and whiteboard system for collaboration

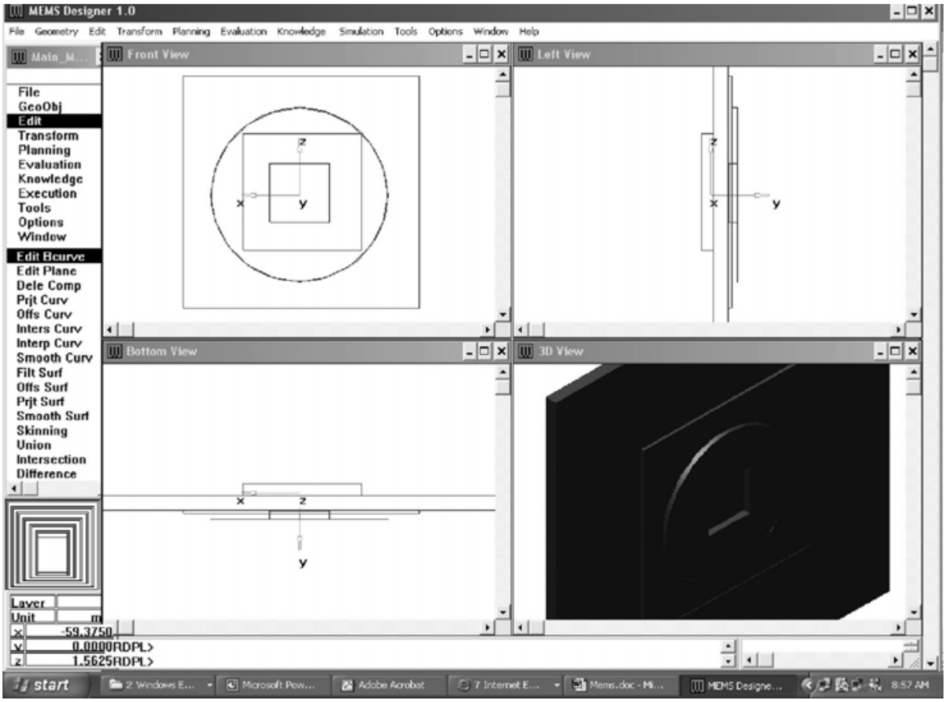

FIGURE 9. MEMS Designer GUI: Standalone and Web Enabled. (a) C++ MEMS Designer Standalone (Flow Rate Sensor Demo)

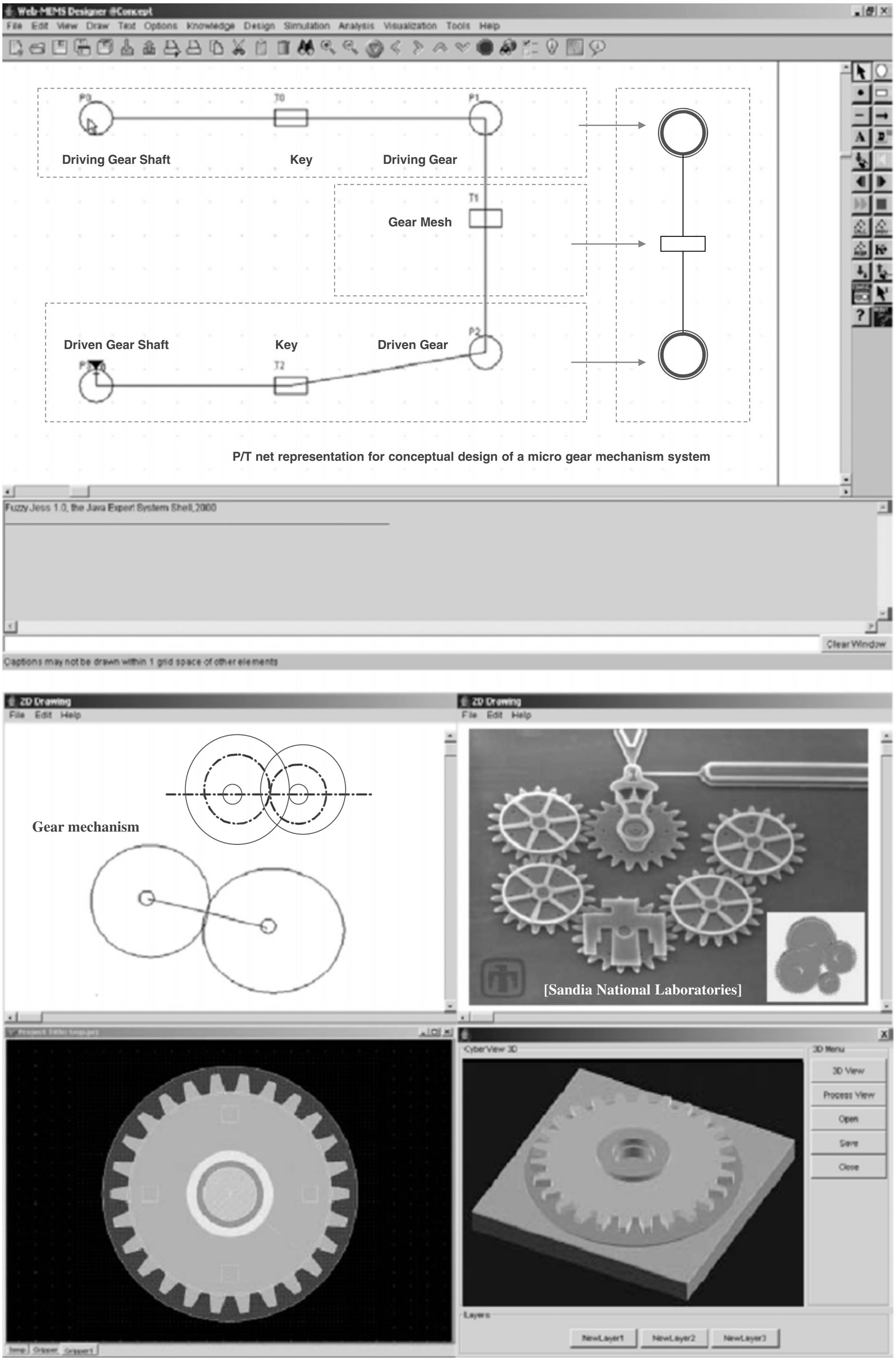

FIGURE 9b. Java Web-Enabled MEMS Designer @Concept GUI (Gear Mechanism Demo)

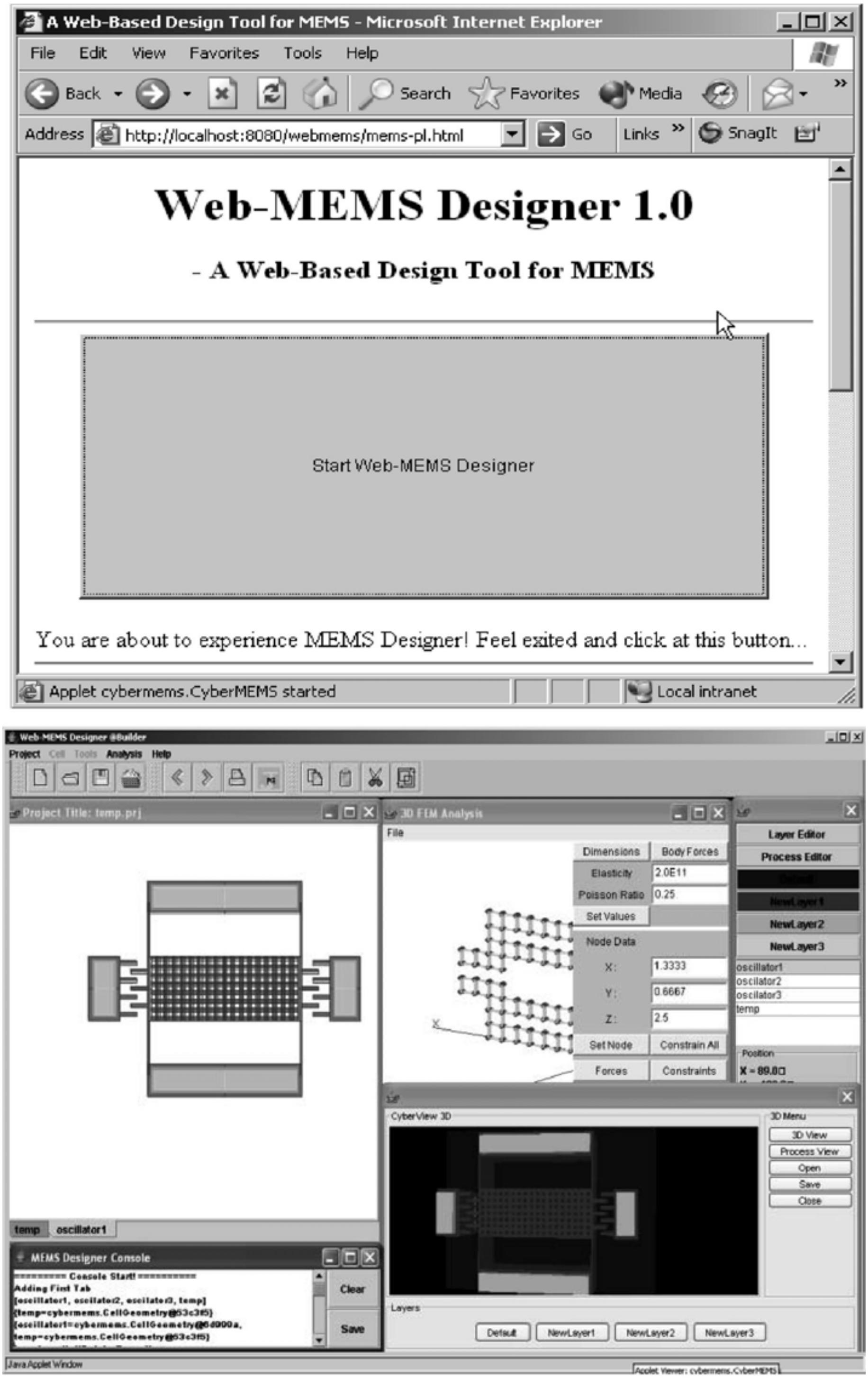

FIGURE 9c. Java Web-Enabled MEMS Designer @Builder GUI (Demo)

MEMS Designer GUI both as a standalone and as an applet. Figure 9(a) is a design screenshot of flow rate sensor using C++ MEMS Designer standalone; Figure 9(b) illustrates the conceptual design of micro gear mechanism using the MEMS Designer @Concept; Figure 9(c) gives screenshots of Java-based web-enabled MEMS Designer startup and design for an oscillator by Web-MEMS Designer @ Builder.

The GUI interacts with designers' events and requests to the DMME server that provides the back-end implementation for the modeling of design problems. The core of the server is based upon object modeling and evaluation (OME) kernel [35, 36] written in Java/Java3D/JDBC, integrating Jess/FuzzyJess. The back-end implementation for knowledge server, including DMME server, and model base server, and the front-end interface to the GUI are written in Java. The DMME server manages each design session in a workspace and can simultaneously maintain several workspaces. The workspace manages administrative aspects of a model (e.g., ownership, access privilege, links to other workspaces in different DMME servers, etc.). The DMME server itself is a CORBA-compliant distributed object and can communicate with other DMME servers. The model base server maintains persistent storage for models created by the DMME servers. The model repository stores a model in a model definition file (MDF) with two parts: meta definition and model definition. The meta definition contains the information such as model id, ownership and access privilege information. The model definition is based upon a model definition language (MDL) used by the system. The core knowledge engine includes knowledge base and problem-solving paradigm (inference engine). The knowledge base is built in Java/Jess. The Web database system is developed by use of Microsoft Access or MySQL databases to store the details of data and Java programs to access these databases through JDBC connections [58, 68].

To enable real-time communication/talking among customers, designers and manufacturing engineers, Windows NetMeeting is incorporated into KS-DMME and used as a video design conferencing tool. The whiteboard system is implemented in NetMeeting. Using the chat function of NetMeeting, designers/ users can talk to and discuss with customers, other designers, and manufacturing engineers for any issues. Using the program sharing function of NetMeeting, designers/users can also share the CAD system with manufacturing engineers to discuss or design the product together in real-time. If designers/users share an image editing software, such as the Microsoft Paint, and import the image file of object (module, product variant, family), then they can mark it up, and discuss any issues.

6. CASE STUDY: COLLABORATIVE DESIGN FOR A MICROGRIPPER

To illustrate the application of the developed Web-MEMS Designer system for collaborative MEMS design process, a working case of a microgripper design for a micro-robotic assembly system was carried out. The design case originated from [9, 55]. It was chosen because of its interdisciplinary and developing nature. The research results from this particular case could be generalized to cover other designs that require collaboration and integration of multiple domains. The focus of the illustration is on how designers from different teams, divisions, or companies in remote locations may participate to create an integrated design model for the microgripper design.

6.1. Problem Definition

Currently, the most common technique used to fabricate MEMS devices involves some form of a lithography-based micro-fabrication method with little or no little assembly. MEMS products manufactured utilizing this technique are accelerometers, and inkjet printer heads. However, certain micro systems or parts cannot be manufactured using MEMS techniques. MEMS devices that have incompatible processes, different materials, or complex geometries, have to be ‘assembled’. Assembly practices require that a human operator pick and place micro-parts manually using high power microscopes and microtweezers. This method of assembly is tiresome, time consuming, unreliable, and costly. The term ‘micro assembly’ is used to describe the assembly of micronsized parts that are extremely small (in the order of 10^{-6} meters). As manual assembly of micro devices is extremely difficult and tedious, there is a need to design computer-controlled approaches to facilitate rapid assembly. In this context, the design of automated or semi automated environments for micro assembly applications become important. Innovative computer based automated assembly methods must be developed to increase efficiency, reliability, and reduce cost. One of the long-term goals of this research is to develop an integrated physical and virtual assembly system to support the design and analysis of candidate assembly and manipulation. The scope of discussion in this chapter is restricted to the design of the micro robotic assembly work cell to support the assembly of micro devices. The emphasis of discussion is on the distributed collaborative design of microgripper used for micromanipulation/micro assembly.

Suppose that designers from different teams, divisions, or companies in remote locations would like to participate in designing a micro-robotic assembly work cell. The micro robotic assembly work cell discussed consists of four major components: the robot system, the micro-positioning stages (work platform) for work piece, a micro-gripper used for manipulation, micro sized parts to be assembled, and microscope with camera to provide guidance and visual feed back, as illustrated in Figure 10. The microgripper could be used as a tool in micro assembly and micro measurement in the micrometer scale.

We use the developed system to carry out collaborative design of the micro robotic assembly work cell. We first decompose the robotic system design problem into modules and define how these modules are related to one another to create the model of a robotic system design problem. The relationships among these modules specify how outputs of a module are connected to inputs of other modules. Then, we use the distributed module modeling and evaluation (DMME) approach to carry out the distributed collaborative design of micro robotic manipulation systems and microgripper used for micromanipulation under the system support.

6.2. Collaborative Micro Robotic System Design Process

Generally, a micro-robotic assembly system consists of three major parts: a micro-robot system, an assembling platform, and micro-components to be assembled. A micro-robot system is generally composed of a micro-robot body and its end-effector with a microgripper. Thus, the overall topology of the design problem and the design workspace can be illustrated in Figure 11. As shown in Figure 11, the micro-robot and microgripper manufacturers provide their design and simulation models to the micro-robot system designers who in turn

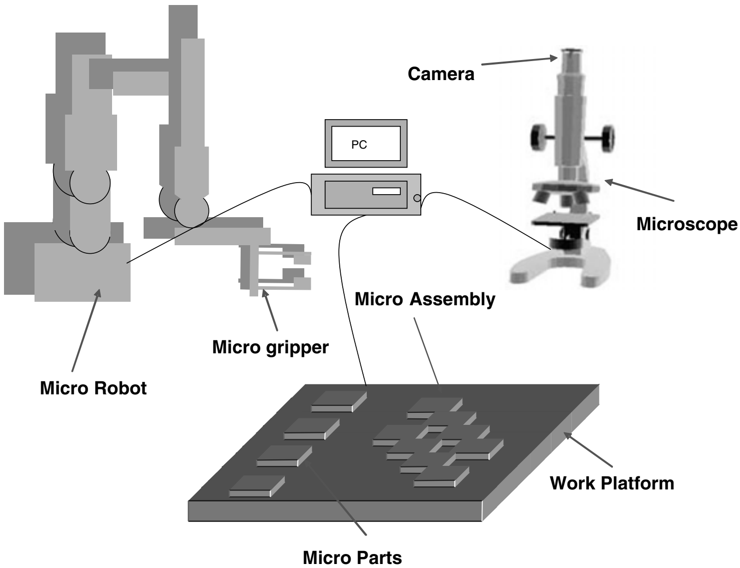

FIGURE 10. Concept of the micro robotic assembly system

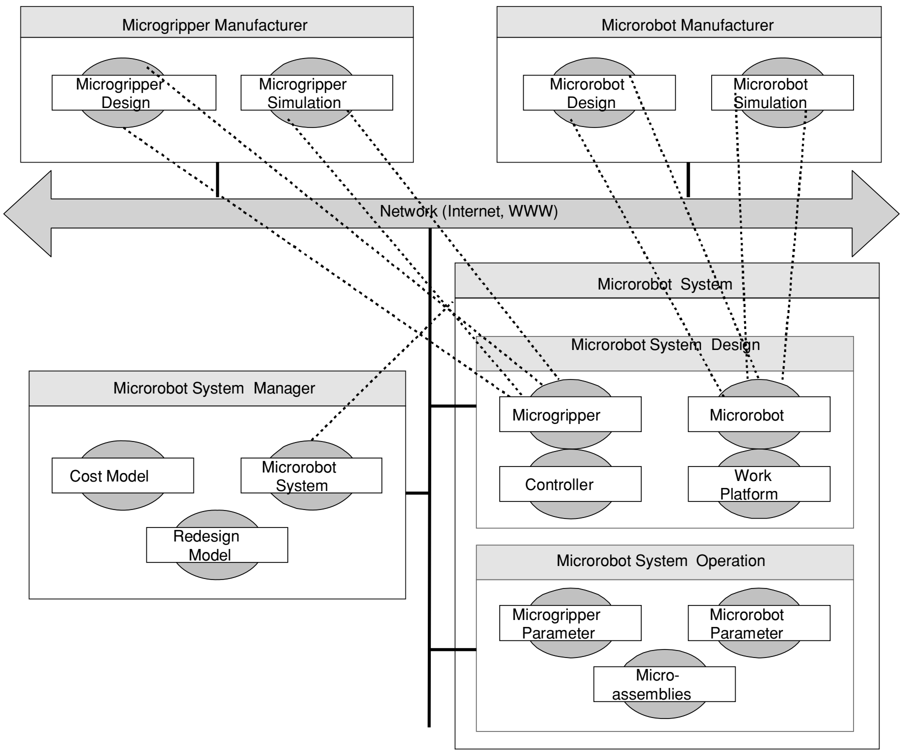

FIGURE 11. Problem topology of the micro-robot system design model

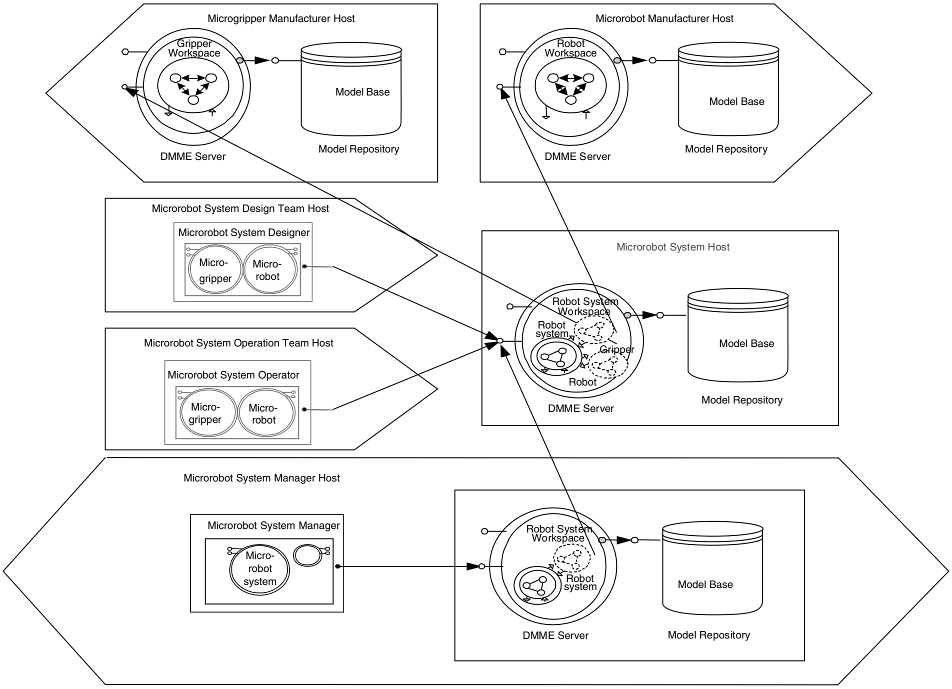

FIGURE 12. Shared design workspace as viewed by the robotic system designers and operator; robotic system manager model connected to the robot system design model

develop the technical models for the micro-robot system. The micro-robot system manager collaborates with the micro-robot system designers and provides models and data for micro-robot operating conditions and requirements. Then, he/she uses the micro-robot system design models created by the micro-robot system designers to develop cost evaluation and redesign models. The microgripper and micro-robot manufacturers develop models for their products so that their customers can obtain performance predictions and evaluations for different parametric configurations and operating conditions. These individual models are constructed, published and served by different companies, as shown in Figure 12. If a single designer or company creates all these models and provides all those services the design work is carried out in an individual workspace, as illustrated in Figure 13.

The design session GUI of Web-MEMS Designer creates and depicts the layout and construction and simulation models or modules in the microgripper design workspaces. Designers can use any commercial web browser to access and work on these modules. Since users/customers will connect to these models to assess the performance of their products, designers should decide how to publish these models, i.e., what simulation services the models offer given appropriate input information. When a model is published anyone can use its services if he/she has the appropriate access privileges. The owner of the model can or may want to conceal knowledge intensive engineering formulae or supply chain information embedded in the model. Through service publication, a designer sets access privilege levels for the services of each module in their workspace. Therefore, the designer

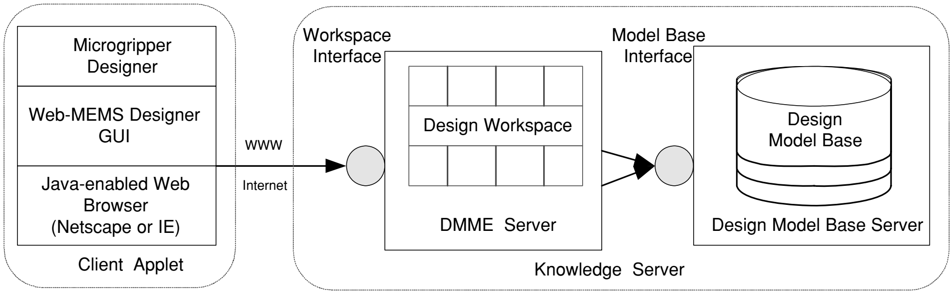

FIGURE 13. Individual workspace for single microgripper designer

working on the design model is assigning access privileges to the services that modules can provide.

As the robot system design and operation are tightly coupled, it would make sense for designers in these groups to share a common model. Thus, while designers from different groups are in remote locations, they can access into the same workspace, which is referred as a shared workspace. Figure 12 shows the design workspace as viewed by the designers from the robot system design team and the robot operation team. The robot system design team is connected to the robot and gripper manufacturing teams so that their robot system design integrated with gripper and robot models can be tested. In this implementation and demonstration, the robotic system is assembled through the use of predefined fixed types of modules (joint modules and link modules) in distributed module inventories (repositories). These modules are published and can be accessed.

Since the micro robot system design and operations are tightly coupled, it would make sense for designers in these groups to share a common model. Therefore, while designers from different groups are in remote locations, they can access into the same workspace, which is referred as a shared workspace. Figure 12 shows the design workspace as viewed by the micro-robot system designers and operation designers. The micro-robot system designer is connected to the microgripper and micro-robot manufacturers. The micro-robot system designer can test their micro-robot system design integrated with microgripper and micro-robot models. In this implementation and demonstration, the robotic system is assembled through the use of predefined fixed types of modules (joint modules and link modules) in distributed module inventories (repositories). These modules are published and can be accessed. The users or operation team can share their workspaces with the design team. The design team creates modules in the upper left corner while the robot system operation team makes the rest design. In this case the design team owns the session and the operation team join as a builder. Although builders cannot modify the modules created by other builders or owners, they can add new modules and utilize all services. For example, the operation team can use a service from a design module to obtain the robot accuracy and the open distance of the gripper and can build new modules in the workspace that utilize this information.

Similarly, the design team can also use services from the models published by the robot and gripper manufacturing team. Utilizing models provided by other designers is referred to as subscribing to a model. It is the responsibility of the design team to provide these data or to locate other models that can provide these data as services. The robot system managers want to evaluate the design from in term of costs and they may link their models to the design module to obtain the information services needed by their models. The design team has only published cost related aspects of their models. This means that the robot system managers can only observe elements of the design models that were published, as the designers wanted to protect their proprietary models.

The microgripper analysis and simulation and the microgripper design are also tightly coupled so that the designers from different design and simulation groups may also need to share a common model and access into the same workspace, although these groups may be in remote locations. The micro-assembly system is operated by means of a virtual micro-robot manipulation system in which 3D models of the micro-components are manipulated virtually in a computer graphics constructed by VRML in the web scheme. The micro-assembly system simulator developed by the simulation team provides a new design tool of 3D MEMS by combining the possibility of the flexible assembly and the intuitive operations. Designers in the design team can use this tool to carry out the intuitive operations and simulations. This can help the designers to verify the design. When a simulating assembly or operating sequence is running, users can control microgripper open-close states, micro-robot positions and orientations, micro-components positions and orientations by clicking on them. The user interface graphically displays micro-robot configurations, microgripper states, and the component states. The simulation results also help the designers in the design team to modify/redesign the design if necessary.

6.3. Collaborative Microgripper Design and Analysis

As discussed above, the microgripper is one of the important components in the micro robotic assembly system. In the collaborative design of mircogripper, many considerations and constraints should be emphasized and negotiated among designers on how to make sure the sensor could work well and the signals could be transferred back without any problem. Figure 14 depicts a mask layout, 2D & 3D model and elastic simulation model for the gripper. Figure 14a shows the shape design of the microgripper. It is a symmetric structure consisting of six beams and four compliant linkages. In operation, the electricity current is applied to the beams of the thermal extension element. The beam heats up and lengthens, causing an angular deformation in the compliant mechanism and then open the gripper tips. Normally, the gripper is in its close position. Adding and switching off the voltage on the thermal extension element can open/close the gripper and thus an object can be gripped. Details can be found in the literature [9, 55].

Since the whole structure is symmetric, only half of it needs to be analyzed. The open distance of the microgripper mostly depends on the compliant mechanism part. Several parameters, including the widths and lengths of the linkages and the distance between the two linkages, influence the final function of the mechanism. The relationship between these parameters and the open distance is studied (see Appendix A). The algebraic equations for the description of the parameters, the relationships, and the conditions under which they apply facilitate dealing with the process of parametric design of microgripper in a systematic and efficient manner. Here, design diagram, a graph representation [23], is used, which is more effective for depicting the parameters and parameter relationships involved in the design. Furthermore, design diagrams bridge the representational gap that usually exists and provides a standard procedure. Constraint nets and data-flow graphs are closely related representation methods.

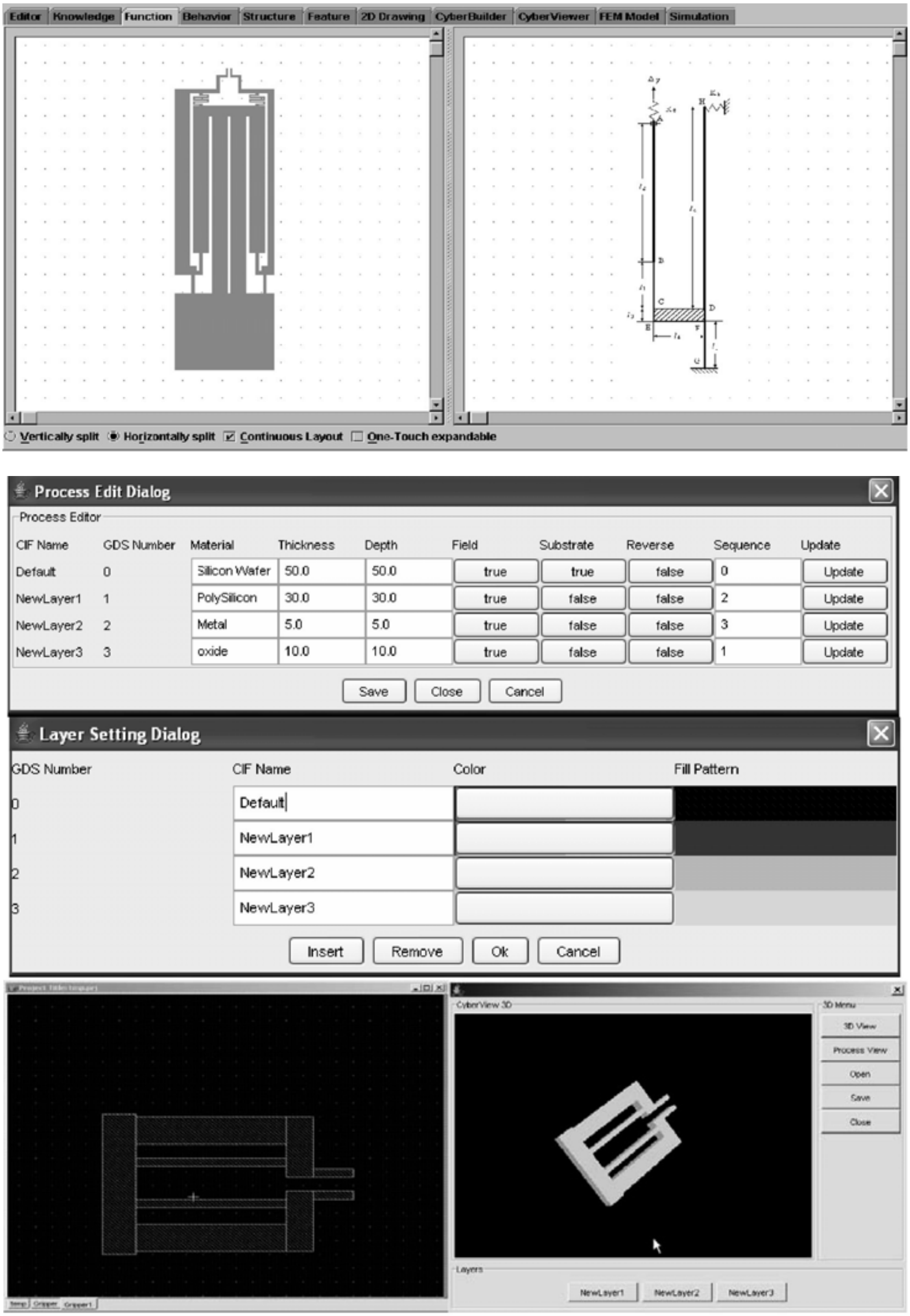

FIGURE 14. Microgripper design and simulation: mask layout, 3D model and elastic simulation model, (a) Layout and elastic simulation model, (b) Mask process and the generated 3D model (Java3D) (simplified demo)

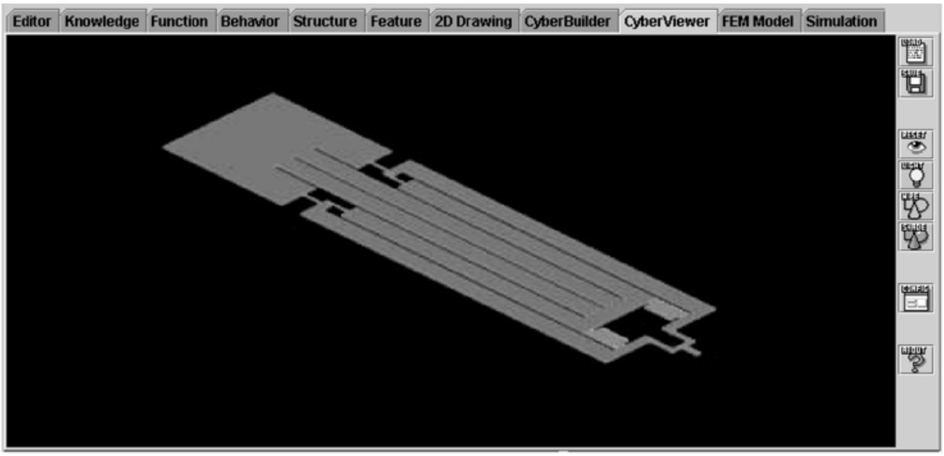

FIGURE 14c. Cyberview of the generated 3D model (VRML)

In the distributed module modeling and design schema, design modules are allowed to make decisions independently on certain parameters identified to be in the control of individual modules; these are decision parameters. Also, values of some exclusive and shared parameters are specified in the design requirements identified as given parameters. The strategy of concurrence can, however, result in conflict in shared parameters (i.e. conflict parameters), due to propagation of given parameters and decision parameters through engineering relationships between the parameters. Resolution of the conflict in values of the shared parameters requires some form of negotiation between the design modules to agree on mutually acceptable values. The classical models of utility and economic negotiation are useful to form the basis for a model of design negotiation. An illustrative situation is shown in Figure 15 in the form of a design diagram, where three modules D_{Mo}, A_{Mo} and E_{Mod} are the design module, analysis module and evaluation module respectively. Figure 16 shows the mesh generation and 2D &3D FEM analysis GUI of the Web-MEMS Designer @ Analysis for the microgripper.

6.4. Decision Support in Collaborative Design

The consultation or decision support session in Web-MEMS Designer for collaborative design was implemented through the application of advisory systems for design support, for example, in assembly method selection, material and process selection, and so on. To illustrate the use of the manufacturing service module in Web-MEMS Designer for material and process selection, an example of a prototype gripper is explored to show the possibilities for making a full production run. Thus, it is necessary to use the process search, material search, and results survey mode [73]. The specifications are made for the procedures of process search and material search. The process search is for the lowest possible cost over a long production cycle. At the end of the process search, Electro-Dischargeable Machine (EDM) (rank 1.00) was ahead of the only other possibility, Etch (rank 0.96). Similarly, after material search, the system generated six viable materials, with carbon steel ranking the highest at 1.00 and aluminum & alloys ranking at 0.98. Furthermore, after process search

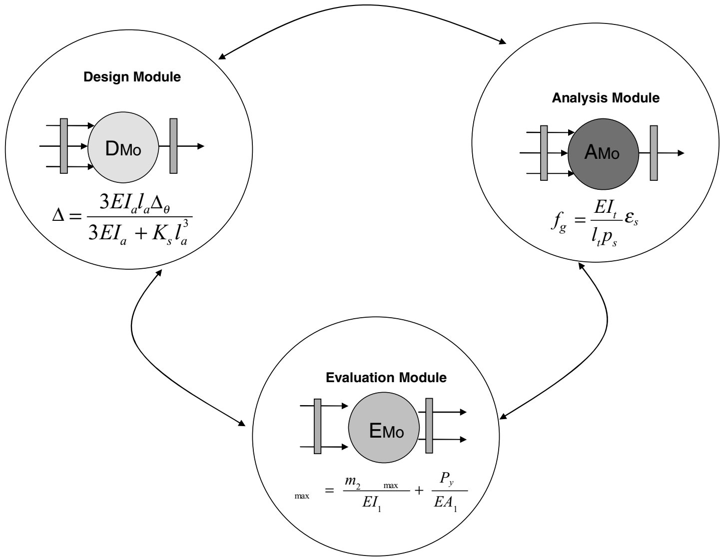

FIGURE 15. Microgripper design and analysis module network

and material search, the “Final Result” button would be enabled and clicked to combine the results of both searches to find the best material/process combination. As shown in Figure 17, the two boxes at the top is a summary of the viable materials and processes, and the final box lists all of the feasible combinations, taking into account a compatibility factor between each process and material. Thus, EDM with carbon steel is the best choice, with etched stainless steel second.

On completion of the reasoning process, Web-MEMS Designer returns the score obtained for this design with respect to this attribute and indicates in the result page the Pass/Fail status of each design parameter. To request an explanation of the evaluation, the user can click on the button of the “Explain the Result” on the results’ page shown above. The explanation may consist of the rationale for the score in terms of justifications and references, both to the design literature and various on-line resources. It also shows an example of how on-line expert design knowledge and resources can be accessed during the design process.

7. SUMMARY AND FUTURE WORK

This chapter presented a web-based design platform for supporting collaborative MEMS design over the Internet and web. A two-tiered client (browser) / knowledge server architecture was adopted to allow experts and designers to publish and subscribe modeling services on the web. The proposed KS-DMME framework is built upon to provide module network architecture for integrating modeling services. In the module network, design resources, models, data, and activities are not centralized nor concentrated in one location. They are distributed among many companies, designers, or design participants working

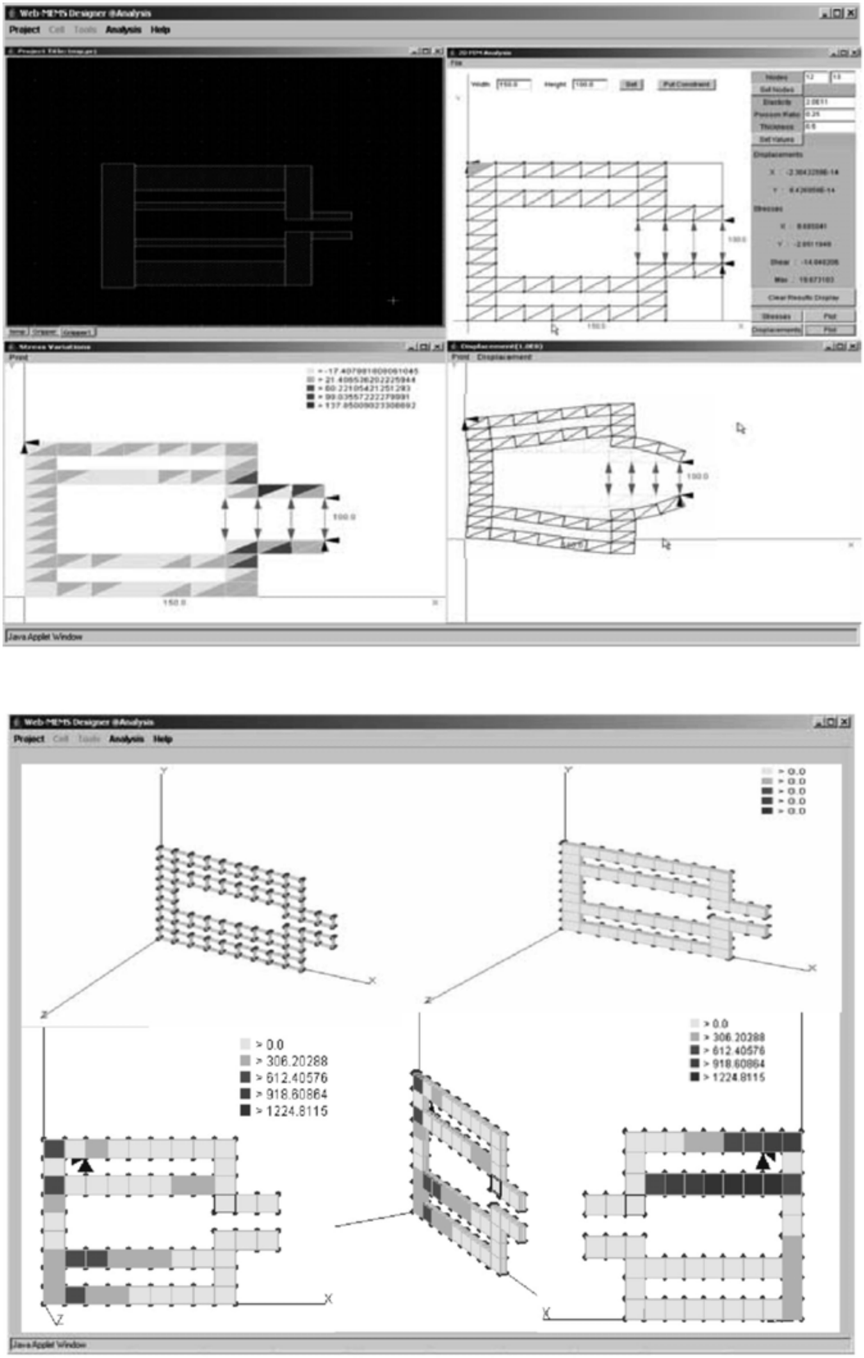

FIGURE 16. Microgripper 2D and 3D FEM analysis by Web-MEMS Designer @ Analysis (Demo), (a) 2D FEM analysis, (b) 3D FEM analysis

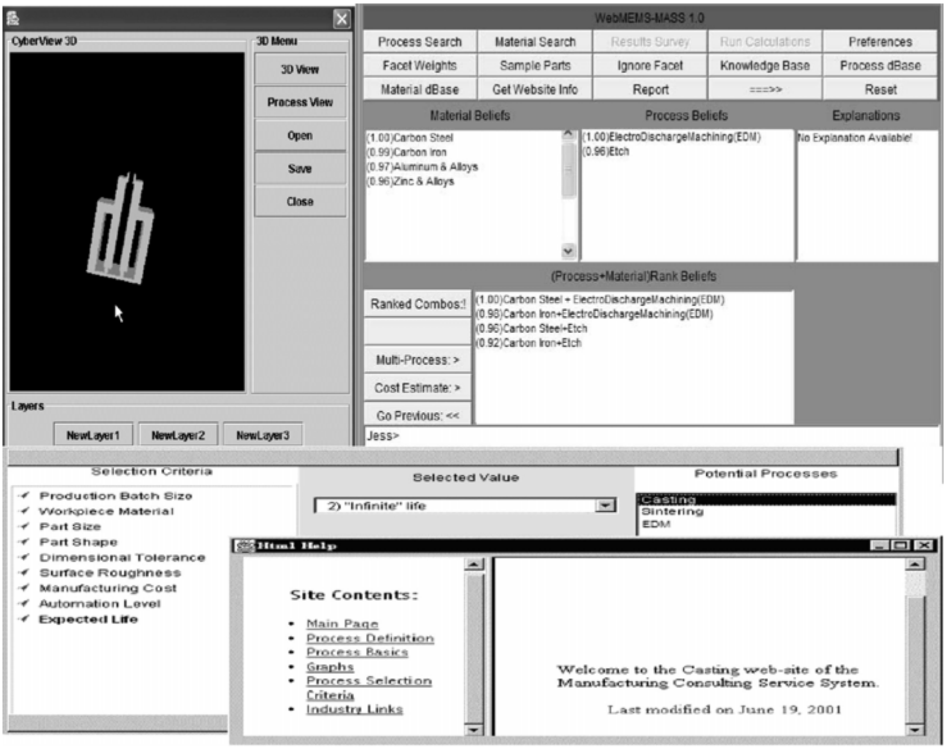

FIGURE 17. Process and material search in the design process and final results

together over the internet/intranet. When module services are connected, the resultant service exchange network creates a concurrent integrated system model or a module network that invokes a chain of service requests if needed to provide correct information. To provide distributed designers with a tool for collaboratively building the concurrent integrated design system models, the KS-DMME framework is extended to be a computer network environment focusing on the design and simulation for MEMS. MEMS design modules are created by fully implementing the locally defined modules and subscribing to the services of remote modules. The implementation of Web-MEMS Designer system hides the details of the remote interaction mechanism from the user but allows the MEMS designer to model interactions between local and remote modules in a transparent manner. In turn designers can selectively publish modeling services for use by others. The microgripper design for micro-robot assembly example illustrates the concept and different models of collaboration supported by the prototype implementation.

The knowledge supported design system can help companies capture and archive their design knowledge and manage the design process. It also supports communication and teamwork by sharing the most up-to-date design information. Designers, especially novices, can benefit from retrieval of knowledge about previous designs by abstracting information and applying it to a new design or by gaining insight into how an earlier related product was designed. By making use of the design knowledge, companies are expected to improve the design process for more innovative products and reducing product development cycle time. As a kernel of the knowledge supported design system, the design decision support system can help design teamsmake better decisions.

The preliminary implementation of the Web-MEMS Designer system illustrates the potential of KS-DMME framework for MEMS design and simulation. When fully implemented and integrated with other computer-based collaboration tools, the Web-MEMS Designer system will provide designers with a powerful infrastructure for collaborative MEMS design. However, there exists a large amount of work to be done both on the particular design paradigms or methodologies for MEMS and the system development. For example, the framework should accommodate top-down and bottom-up approaches or models in the context of both traditional sequential design processes and concurrent design for MEMS devices or systems. In a collaborative design environment, there are also a number of fundamental issues yet to be addressed such as knowledge base evolutionary maintenance, model interface standard, computational strategy for resolving circular dependencies in the DMME model, parallel service request invocation, etc. In addition, other aspects such as human interaction and knowledge sharing will still require the integration of additional support tools with the framework (e.g., ontology, etc.). The project described in this chapter is still in progress.

8. DISCLAIMER

The bulk of the work reported here by the author was conducted during his tenure at Nanyang Technological University, Singapore. 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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APPENDIX A: ANALYSIS OF MICROGRIPPER

The analysis of the microgripper is based on the work [9, 55]. In the model shown in Figure 12a, the expansion element is replaced by a spring with stiffness K_e, and $K_e = EA_e/l_e$, here E is the Young's modulus and A_e and l_e are cross-section area and length of the thermal extension element. The transfer element and the two compliant linkages are treated as Euler beam. Because the two linkages have the same functions, they should have the same dimensions. As the figure shows, one linkage is fixed on the basement and a small displacement in Y direction is inputted at the end of the other one. A much shorter and wider beam connects the two compliant linkages, and thus the beam can be considered as a rigid body. The gripper arm is also treated as an Euler beam and another spring with stiffness coefficient K_s is used to simulate the supporting spring structure.

Figure A1 shows force condition of the connector beam. From the force equilibrium principle, it can be known that the forces added on point C and F should have the same values and opposite directions. m_1 and m_2 are the moments added on the connector beam by the linkages. The sum of the moments on the beam should be zero, therefore,

$$m_1 + m_2 + l_3 P_x - l_4 P_y + K\Delta_\theta = 0 \tag{A1}$$

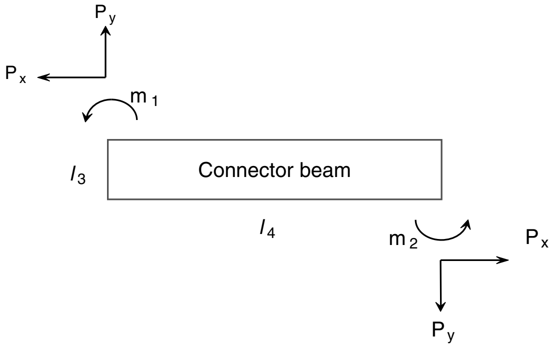

FIGURE A1. Force illustration of the connector beam

where, Δ_θ is the rotation angle of the connector beam and K represents the equivalent rotation stiffness of the gripper arm at point D and should be

$$K = \frac{3EI_a K_s l_a^2}{3EI_a + K_s l_a^3} \tag{A2}$$

where, I_a and l_a denote the second moment of area and length of the arm. As the rotation angle Δ_θ is normally only a small value [55], $sin\Delta_\theta$ can be considered the same as Δ_θ, $sin\Delta_\theta \approx \Delta_\theta$. In this case, the difference between the x-coordinates of point C and F reduces $l_3\Delta_\theta$ and the difference between the y-coordinates of point C and F increases $l_4\Delta_\theta$. Thus,

$$\begin{aligned} &-\frac{1}{2}\left[\frac{1}{EI_1}l_1^2 + \frac{1}{EI_2}l_2(2l_1 + l_2)\right]m_1 - \frac{1}{2}\frac{1}{EI_1}l_1^2 m_2 \\ &+\frac{1}{3}\left[\frac{2}{EI_1}l_1^3 + \frac{1}{EI_2}\left(l_2^3 + 3l_2^2 l_1 + 3l_2 l_1^2\right)\right]P_x - l_3\Delta_\theta = 0 \end{aligned} \tag{A3}$$

and,

$$\left(2\frac{1}{EA_1}l_1 + \frac{1}{EA_2}l_2 + \frac{1}{K_e}\right)P_y + l_4\Delta_\theta = \Delta_y \tag{A4}$$

where, I_1, l_1 and I_2, l_2 represent the second moment of area and length of the linkages and the displacement transfer element respectively. The ends of beam BC and beam GF should also rotate Δ_θ and they can be considered as cantilever beam, then m_1, m_2, P_x and Δ_θ should have the following relationship,

$$\left(\frac{1}{EI_1}l_1 + \frac{1}{EI_2}l_2\right)m_1 - \frac{1}{2}\left[\frac{1}{EI_1}l_1^2 + \frac{1}{EI_2}l_2(2l_1 + l_2)\right]P_x - \Delta_\theta = 0 \tag{A5}$$

and

$$\frac{1}{EI_1}l_1 m_2 - \frac{1}{2}\frac{1}{EI_1}l_1^2 P_x - \Delta_\theta = 0 \tag{A6}$$

This means the rotation angle Δ_θ is generated by the combination of the moment and the force.

In total, there are five variables, namely m_1, m_2, P_x, P_y, and Δ_θ and we have five equations (A1)–(A6). Hence, if the geometric dimensions of the microgripper are determined, these variables can be found, and then the open distance can be calculated out as

$$\Delta = \frac{3EI_a l_a \Delta_\theta}{3EI_a + K_s l_a^3} \tag{A7}$$

Further, to evaluate the strength of gripper, the location and the value of the maxim strain need to be determined. In this design, deforming some certain parts transfers the displacement, and the strain is concentrated mainly in the two compliant linkages. The two linkages have the same rotation angles at their ends, and the rotation stiffness of the beam FG is stronger than the stiffness of the combination of beam BC and beam AB. Therefore, m_2 should be bigger than m_1 and the maximum strain occurs at the left side of the beam FG as follows:

$$\varepsilon_{\max} = \frac{m_2 \rho_{\max}}{EI_1} + \frac{P_y}{EA_1} \tag{A8}$$

where, ρ_{max} should be half of the width of the beam FG. The gripping force can be expressed as

$$f_g = \frac{EI_t}{l_t \rho_s} \varepsilon_s \tag{A9}$$

where ε_s denotes strain of the piezoresistive film, I_t and l_t denote the second moment of area and length of the tip and ρ_s denotes how far the piezoresistive film is away from the central line of the tip.

APPENDIX B: GENERIC P/T NET FOR MICRO ASSEMBLY REPRESENTATION AND CONCEPTUAL MEMS DESIGN

A generic graph can be described as a two tuple G = G (V, E), where V is the set of nodes and E is the set of connecting arcs which link between nodes. If each arc in a graph has a direction, then the graph is a directed graph. If a node is categorized into two classes: place (P) node and transition (T) node, then a place-transition (P/T) net graph model, as shown in Figure B1 (a), can be formally defined as: PTN = {P, T, A, W}, where, $P = (p_1, p_2, \ldots, p_m)$ is the place node set; $T = (t_1, t_2, \ldots, t_n)$ is the transition node set; and A is a arcs set which links between place node and transition node, and has the characteristics of : $P \cap T = \phi$, $P \cup T \neq \phi$, and $A \subseteq (P \times T) \cup (T \times P)$; and W: $A \rightarrow \{0,1\}$ is an association weight function on arcs, $\forall a \in A$, $W(a) = w_i$, w_i is the weight of arc a. Correspondingly, if each arc in the P/T net graph has a direction, then it becomes a directed P/T net graph, as shown in Figure B1(b).

Based on the definition, a Petri net consists of places (P) and transitions (T), which are linked to each other by arcs. Therefore, a Petri net graph is in fact a directed P/T net graph. If the net activities are based on a vision of tokens moving around an abstract network, in which

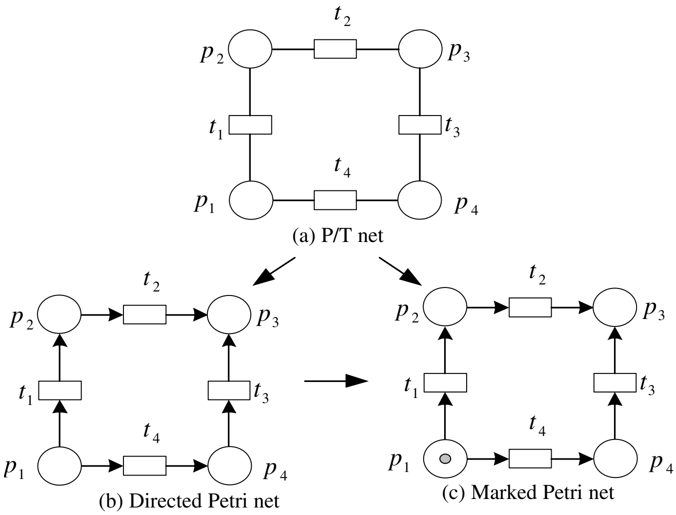

FIGURE B1. Generic P/T net graph

tokens are conceptual entities that model the objects and appear as small solid dots moving in a real network, a marked Petri net, as shown in Figure B1(c), can be formally defined as a 5-tuple, PN = (PTN, M_0) = (P, T, A, W, M_0), where, PTN is a directed P/T net; P, T, W, A are the same as above definitions; M_0: P $\rightarrow \{0,1,2,\ldots\}$ is the initial marking. The Petri net graph is a graphic representation of Petri net structure and visualizes the reasoning rules.

By the generic P/T net scheme, we mean that a P/T net model of a problem is first described as a kind of "template", and the models of the particular sub-problems are then established as instances of the template. Since incorporating a P/T net model into a general problem description scheme in AI generates the proposed generic P/T net, existing AI-based problem solving strategies such as search, reasoning and (fuzzy) expert systems are applicable for the generic P/T net modeling and analysis. Thus, the generic P/T net is knowledge intensive, also called knowledge P/T net. For more descriptions, please refer to [70, 71].

As an assembly is composed of parts or components and connectors (joints), and a single part is composed of physical features, the different levels of assembly actually form a hierarchy, which utilizes the relationships between different parts of assembly and even different features of part. The "place-transition" (P/T) model is used to represent the mechanical systems and assemblies, in which each part is represented as a place and each connector (joint) is represented as a transition. Therefore, a mechanical system or assembly can be viewed as a hierarchical P/T net, called Assembly_Model, and accordingly a subsystem or subassembly is a sub P/T net. Using modular representation, a sub P/T net (object) can be described as either a macro place or transition. This is mainly dependent on its function as either a component or a joint or a connector. Token data abstraction and dynamic distribution can be used for knowledge representation in describing the structure and system state changes. In addition, the generic P/T net can be used for intelligent modeling of assembly functions and behaviors, and design, planning and simulation of assembly processes and assembly systems.

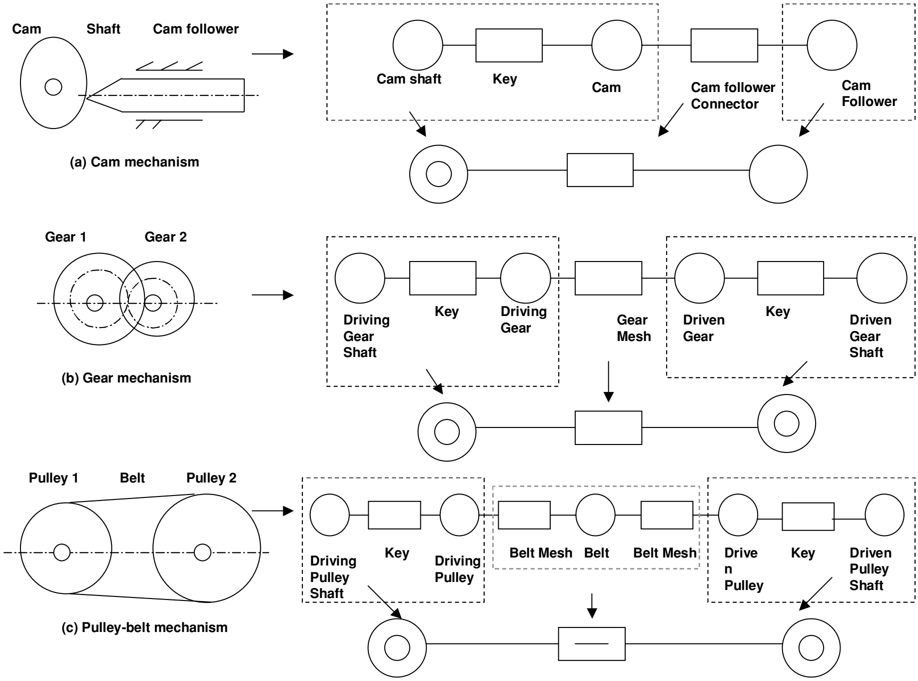

FIGURE B2. P/T net-based representation for micro primitive mechanisms

A multi-level P/T net could be generated by network modeling from top to bottom. Any conceptual design product can be considered as a combination of places and transitions. Transitions make places work normally by connecting them. Each primitive mechanism can be viewed as a micro place node or micro place node in the P/T net-based hierarchical structure of the mechanical product. Each primitive mechanism can also be represented by a P/T net. Figure B2a, b and c show a P/T net-based representation of three primitive mechanisms (Cam, gear mesh, and pulley-belt), respectively.

P/T net model could also allow for the possibility that the properties take some values in the form of a fuzzy set over a base range. For example, a transition with a motion transmission function might become a gear pair; a transition with a fixing function might be a collection of geometric mating surfaces such as a cylinder and shoulder. Since places and transitions for components and connectors are conceptually fuzzy, they might form a fuzzy P/T net to represent a sub-assembly during later stages of design.

APPENDIX C: MEMS MODELING AND SIMULATION RELATED WEBSITES

3-D Modeling and Simulation
ANSYS (http://www.ansys.com/products/multiphysics.shtml)
CFD Research Corporation (http://www.cfdrc.com/datab/Applications/MEMS/mems.html)
IntelliSuite (http://www.intellisuite.com/)

MEMCAD (http://www.memcad.com)
FlumeCAD(http://www.flumecad.com)
SESE (http://www.nmtec.ch)
Solidis (http://www.ise.ch)

Coyote Systems (http://www.coyotesystems.com/applications/applications.html)
IntelliSense Corporation (http://www.intellisense.com/software.html)
Microcosm Technologies, Inc. (http://www.memcad.com/products.html)
Stanford University (http://www-tcad.stanford.edu/tcad.html)
University of Illinois (http://galaxy.ccsm.uiuc.edu/mems_research.htm)

Reduced Order Modeling
Analogy (http://www.analogy.com/Mixed/default.htm)
Duke University (http://www.ee.duke.edu/Research/IMPACT/)
Massachusetts Institute of Technology (http://rle-vlsi.mit.edu/research)
Microcosm Technologies, Inc. (http://www.memcad.com/products.html)
System Level Modeling
Carnegie Mellon University (http://www.ece.cmu.edu/∼mems/projects/memsyn/index.shtml)
University of California—Berkeley (http://ptolemy.eecs.berkeley.edu/)

Tool Suites
MEMSCAP (http://www.memscap.com/)
An's MEMS CAD, http://myhome.dreamx.net/piyo123/default.html
IntelliSense (2001), http://www.intellisense.com/
Jess (1999), http: // herzberg.ca.sandia.gov /jess, Sandia National Laboratories
MEMCAD (2000), http://www.memcad.com/

Other
University of California—Berkeley (http://www-bsac.eecs.berkeley.edu/∼cfm/)
NIIIP (1999), http:// www.niiip.org/
RaDEO (1998), http://elib.cme.nist.gov/radeo/

Anis, http://www.intellisense.com/software/anise.html
SIMODE, http://www.gemac-cheminitz.de/mst/simode.html
MicroCAD, http://www.fuji-rico.co.jp/crab/electric/semicon/microcad/micro.html
SEGS, http://www.design.caltech.edu/Research/MEMS/software.html
SIMPler, http://www-inst.eecs.berkeley.edu/∼ee40/SIMPLer/SIMPLer.html
CaMEL, http://www.memsrus.com/cronos/svcs2tcml.html
LASI, http://cmoseu.com/cmos1/winlasi/winlasi.htm
MAGIC, http://www.research.digital.com/wrl/projects/magic/magic.html
VALCAIN, http://www.memscap.com
MEMS Pro, http://www.tanner.com or http://www.memscap.com
Mentor Graphics, http://www.mentorg.com
Saber, http://www.analogy.com

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