A VISION OF STRUCTURED CAD FOR MEMS

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ABSTRACT

Computer-aided design tools tailored for microelectromechanical systems (MEMS) are needed to enable design of complex systems with multiple energy domains. In an analogy to the VLSI design methodology, physical, structural, and behavioral views of MEMS can be formed and coupled together in an integrated toolset. Of key importance is the formation of parameterized MEMS component libraries to support these views. Fast coupled-domain numerical (physical) simulation and behavioral simulation are required to move freely between the views.

1. INTRODUCTION

One prevailing trend in MEMS is toward monolithic systems where multiple micromechanical devices are integrated with sense electronics, digital I/O, self-test, auto-calibration, digital compensation, and other signal processing functions. There is a growing demand for rapid design, analysis, and synthesis tools for MEMS that include coupling between multiple energy domains, including mechanical, electrostatic, magnetic, thermal, fluidic, and optical domains.

Presently, most development of MEMS involves concurrent design of devices and their associated fabrication processes. More rapid development of MEMS requires a structured design methodology, supporting tools, and supporting model libraries for common MEMS processes. Eventually, MEMS processes that lend themselves to structured design will evolve into *de facto* standards, because it will become easier to design new devices in these processes. One key to rapid design will be the ability to reuse design knowledge through hierarchical component and model libraries.

Structured design methods for MEMS are not completely new; they are borrowed from the VLSI design methodology. CAD for VLSI spans many levels of abstraction from materials, device, circuit, logic, register, to system level. At each of these levels, a design can be viewed in physical, structural (schematic), or behavioral form. Similar design views and hierarchical levels for MEMS are feasible and sorely needed. Analogous hierarchical levels for MEMS up to the VLSI circuit level are easily made. Even higher levels of abstraction, which may be different from the VLSI paradigm, will evolve for MEMS.

Complications with implementing a MEMS design methodology stem from the difficulty in handling the coupled energy domains. A first task in development of structured MEMS design tools is the formation of standard data representations and standard cell libraries. An enormous effort is necessary to identify and to model reusable MEMS processes, elements, devices, and architectures. MEMS CAD tools must be integrated, with appropriate links available to the designer to switch between different lateral views and hierarchical levels.

In this paper, a brief overview of current MEMS CAD tools, design practices, and process services is presented. A vision of structured design and synthesis for MEMS is then given.

2. CURRENT MEMS CAD TOOLS

Several groups have existing research programs to address the deficiency in MEMS design tools. Examples from the U.S. include MEMCAD (M.I.T. [1][2], Microcosm [3]) and CAEMEMS (Univ. of Michigan)[4]; examples from Europe include CAPSIM (Catholic Univ. of Leuven, Belgium)[5], SENSOR (Fraunhofer Institute, Germany)[6], and SESES (ETH, Zürich)[7]. These tools involve general numerical analysis of layout and generation of macro-models for simulation.

MEMCAD has evolved into a MEMS modeling framework with rapid self-consistent electromechanical 3D numerical simulation. Recent advances have been made in simplifying the input and visualization

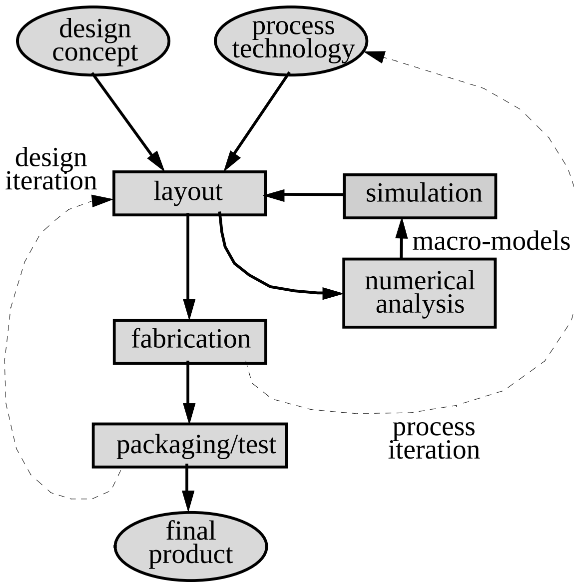

Fig. 1. Flowchart of current MEMS design practice.

of 3D models of micromechanical structures from layout using the MEMBuilder tool [8]. CAEMEMS is a framework in which the users chooses among modules that address specific design domains. CAEMEMS automatically generates a set of parameterized response surfaces by launching multiple finite-element analyses. IntelliCAD[9] available from IntelliSense Corp. is a commercial MEMS CAD tool with automated 3D modeling from layout and process integrated with numerical analysis.

Other commercial tools by Tanner Research[10] cater to the MEMS community by allowing layout of non-manhattan geometry and supplying MEMS technology files with design rule checking. These tools are definite improvements over use of Magic or KIC for layout and stand-alone numerical analysis tools (e.g. ABAQUS, ANSYS, Ansoft Maxwell).

For general MEMS devices, concurrent design of process and structure is important, but there have been only a few efforts to improve CAD in this area. One promising activity at the University of Michigan involves MEMS process synthesis from design specifications [11].

3. CURRENT MEMS DESIGN PRACTICES

Current MEMS design practice, shown in Fig. 1, focuses on iterative device and process development. Design concepts are implemented in a manual layout. The performance is then analyzed using numerical analysis tools, usually resulting in iterations on both the layout and the underlying process. The present state-of-the-art in MEMS CAD relies on device-level extraction of macro-models in a limited set of energy domains for behavioral simulation. Current commercial design tools cannot deal with the complex multi-domain architectures that will be necessary to create the next-generation of commercial MEMS.

Much future work should focus on creating very fast multi-domain numerical simulation tools to ease both process development and device macro-modeling. However, these numerical tools by themselves may not be practical for rapid iterative design since the physical layout (and perhaps the process) must be changed for each iteration without necessarily knowing what to change to best to improve the device performance. Currently, a self-consistent electro-mechanical analysis of even a simple device requires many man-hours to create the 3-D geometry and perform the numerical simulation. Plus, the time to complete a manual design cycle in MEMS has not decreased significantly over the past few years since knowledge from previous development efforts cannot be easily reused by future developers.

4. MEMS PROCESS SERVICES

MEMS covers a broad, evolving spectrum of fabrication processes. In the U.S., two process services are available that produce surface-micromachined MEMS, where the microstructures are patterned out of thin films on the substrate surface. Polysilicon MEMS can be built in MCNC's MUMPs process [12], and laminated oxide/aluminum MEMS can be built using MOSIS followed by an in-house dry-etch release step [13].

There are a several important benefits of making microstructures with stable fabrication services such as MUMPs and MOSIS: 1) sensor fabrication is fast and reliable, so prototypes can be reproduced anytime, 2) all, or most, fabrication steps are done externally, so resources can be invested in design, not standard processing, 3) the process is repeatable and characterized, so circuit and microstructure designs can be re-used, 4) devices improve as the process technology improves (*e.g.* scaling).

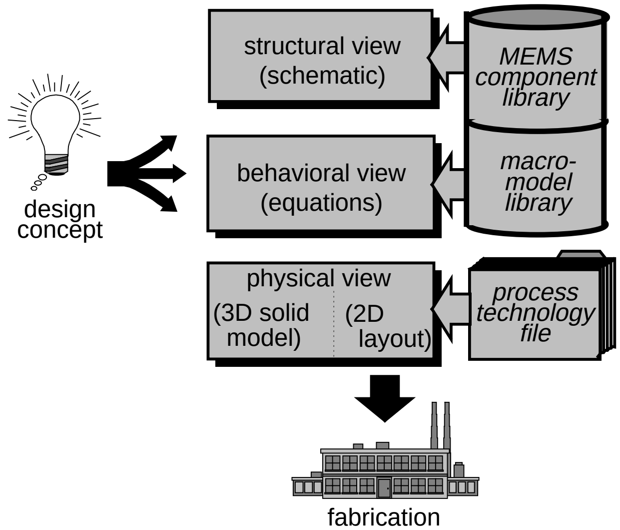

Fig. 2. Parallel views and supporting libraries in the MEMS design and synthesis methodology.

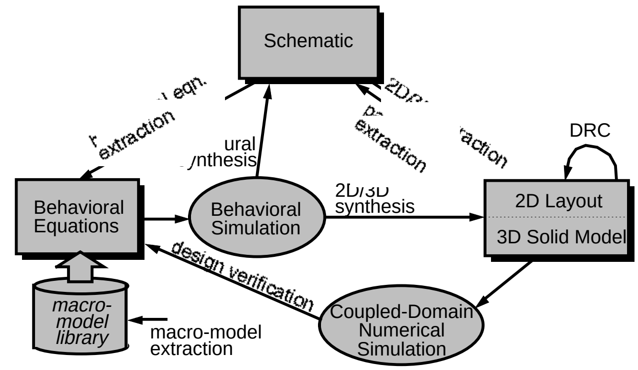

Fig. 3. CAD tools coupling the MEMS schematic, behavioral, and physical views.

5. STRUCTURED DESIGN AND SYNTHESIS

In a complementary approach to existing analysis tools, we are developing circuit-level design and synthesis tools tailored to general surface-micromachined systems. The planar '2 1/2-D' topology of surface-micromachined MEMS lends itself to abstraction at this higher level than that offered by numerical device simulation alone. These tools will increase the performance, complexity, and level of integration designed into such MEMS as inertial sensors (accelerometers, gyroscopes), x-y-z servomechanisms for probe-based data storage, communications circuits (filters/resonators/mixers), displays (micromirrors, light valves), infrared imagers, pressure and tactile sensors, and thermal flow sensors. Once a working structured design methodology is established for surface-micromachined MEMS, the techniques may be extended to other processes, such as bulk-machined Si or a dissolved-wafer process.

The existing IC CAD infrastructure can partially support the circuit-level MEMS design. In contrast to VLSI design, however, MEMS design has a tight coupling between form and function. The inclusion of mixed-signal, multi-domain functionality requires a re-tooling of the IC CAD software to handle the job.

The three parallel views – physical, structural (schematic), and behavioral – for MEMS design are shown in Fig. 2. Design starts with the engineering specifications and concepts. Implementation and evaluation of the concepts are accomplished by moving back and forth between views until a suitable design is found and sent to the process service for fabrication. The physical view can take the form of either a 3D solid model or a 2D layout. The structural view specifies connectivity between micromechanical elements in a schematic. The behavioral view specifies the governing equations of the system, such as electrical node equations, equations of motion, and heat transfer equations. It is important to have the flexibility to move freely between these views.

Most existing surface-micromechanical designs can be partitioned into discrete components which are modeled as lumped-parameter elements, such as beam springs, plate masses, and electrostatic actuators. Conversely, new MEMS devices can be created by connecting together these lumped elements in different configurations, much like analog circuit design is accomplished. Simplified physical and behavioral views of MEMS are currently used by designers, while the schematic view has been missing. The MEMS schematic provides a critical link between the physical and behavioral views and may often be the starting point in design.

Additional key features of the design methodology lie in the integration and automation of coupling between the views, as shown in Fig. 3. These coupling mechanisms include behavioral equation extraction and simulation, structural synthesis, and layout synthesis, layout extraction from schematic, and parameter extraction from layout. An example design session might start with construction of a MEMS schematic, then synthesize layout, extract parasitics, and simulate the mixed-signal response. Depending on the simulation results, an inadequate design may be iterated by modifying the schematic, whereas a suitable design may be verified with 3D numerical simulation. Bi-directional coupling between views must be implemented to support this kind of design flexibility.

Efficient mixed-signal mixed-domain simulation is critical to the iterative design process. Fast behavioral simulation will enable rapid exploration of different design concepts. During the initial iterative design phase, the designer will be freed from doing detailed layout and 3D numerical simulation. Many groups are already exploring behavioral MEMS simulation using device macro-models extracted from numerical analysis.

An enabling feature of future MEMS design systems will be the automation of behavioral macro-model generation from layout. Physically correct and extensible models of microelectromechanical components are essential if one is to simulate, analyze, and synthesize MEMS. If the models are inadequate, the design will fail, regardless of how good the tools are. Efficient multi-domain numerical analysis is critically important for both generating lumped-element macro-models and for verification of final designs. In order to demonstrate the design tools and drive the effort to automate modeling, a core library of elements and models must be developed to support integrated MEMS design. When appropriate, parameterized models should be generalized with links to manufacturing variables to ease the extension to new MEMS process technologies.

6. CONCLUSIONS

An initial wish-list for the MEMS CAD toolset includes:

- standard MEMS data representations and interchange formats
- standard MEMS cell libraries supporting behavioral, schematic, and physical views (*e.g.* materials database, technology files, layout cells, schematic component library, and macro-model library)
- standard MEMS process-module libraries and standard process flows
- process visualization, simulation, synthesis, and technology file generation
- 3D solid model generation, visualization and animation
- fast modeling and verification tools; coupled-domain, numerical analysis (*e.g.* finite-element method, boundary-element method)
- MEMS schematic capture
- mixed-signal multi-level multi-domain behavioral simulation
- layout of arbitrarily shaped objects with design rule checking
- parameter extraction from layout
- layout synthesis and verification
- cross-linking of manufacturing, physical, and behavioral variables

By providing circuit-level representations, MEMS design tools will enable rapid, intuitive exploration and analysis of the design space for large mixed-signal multi-domain systems. The high-level tools will speed up the design cycle from the order of several months to days.

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