Structured Design Methodology for MEMS

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One important trend in microelectromechanical systems (MEMS) is toward monolithic systems where micromechanical devices are integrated with digital I/O, self-test, auto-calibration, digital compensation, and other signal processing functions. There is a growing demand in the MEMS community for rapid micromechanical design and analysis of complex systems involving multiple physical domains, including mechanical, electrostatic, magnetic, thermal, fluidic, and optical domains.

An important question generated in this workshop is: Can structured design methods for MEMS be developed by making an analogy to 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. A similar design hierarchy for MEMS is feasible and sorely needed. Analogous hierarchical levels up to the VLSI ‘circuit’ level are easily made; higher levels of abstraction may evolve for MEMS that are different from the VLSI paradigm. 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.

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

- standard MEMS data representations and interchange formats
- standard MEMS cell libraries supporting behavioral, schematic, and physical views at all levels of abstraction (e.g. materials database, layout cells, schematic element library, and a system macro-model library)
- standard MEMS process-module libraries and standard process flows
- process simulation and visualization
- process synthesis and technology file extraction
- 3D rendering and animation
- 3D generation from layout and technology files
- layout of arbitrarily shaped objects with design rule checking
- layout synthesis and verification
- fast modeling and verification tools; coupled multi-domain, numerical analysis (e.g. finite-element method, boundary-element method)
- parasitic extraction to schematic and behavioral views
- macro-model parameter extraction from physical and schematic views
- multi-domain schematic capture (i.e. schematic view showing connectivity between mechanical, electromechanical, thermal, and circuit lumped-parameter elements)
- mixed-signal multi-level multi-domain simulation

Current MEMS CAD Tools

Several groups have existing research programs to address the deficiency in MEMS design tools. Examples from the U.S.A. include MEMCAD (M.I.T.)[1] and CAEMEMS (Univ. of Michigan)[2]; examples from Europe include CAPSIM (Catholic Univ. of Leuven, Belgium)[3], SENSOR (Fraunhofer Institute, Germany)[4], and SESES (ETH, Zürich)[5]. 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 of 3D models of micromechanical structures from layout using the MEMBUILDER tool[6]. 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[7] 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[8] 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, Maxwell). More effort must be poured into fast multi-domain numerical analysis tools specifically tailored for MEMS design. MEMS process simulation and synthesis tools are needed and are being developed[9], but a discussion is outside the scope of this summary.

Current MEMS Design Practices

Current MEMS design practices focus on physical device and process development. A simplified design methodology is shown in Figure 1. 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 electromechanical analysis of a simple device requires many man-hours to create the 3-D geometry and perform a numerical analysis. The 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.

MEMS Process Services

MEMS covers a broad, evolving spectrum of fabrication processes. This fact makes it very difficult to foresee the ultimate MEMS CAD framework. Our initial efforts at Carnegie Mellon have focussed on design tools for surface-micromachined MEMS, such as polysilicon MEMS built in MCNC's MUMPs process[10], and laminated oxide/aluminum MEMS built using MOSIS followed by an in-house dry-etch release step[11]. There are a several important benefits of making microstructures with stable foundry services such as MUMPs and MOSIS:

- sensor fabrication is fast and reliable,

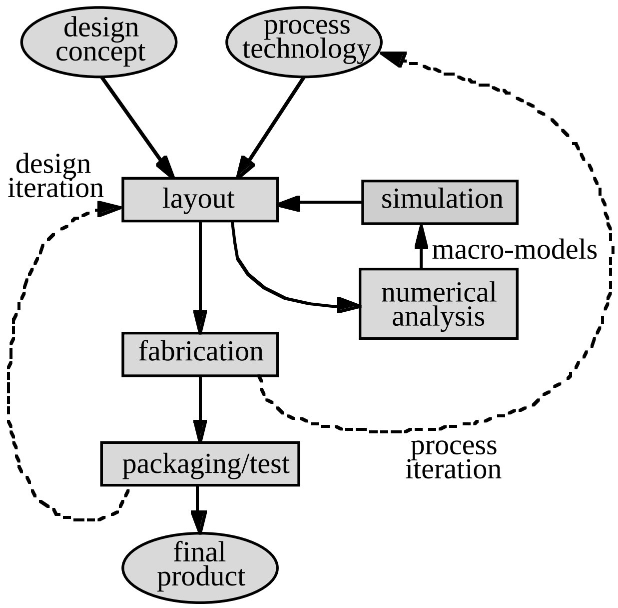

Figure 1. Flowchart of current MEMS design.

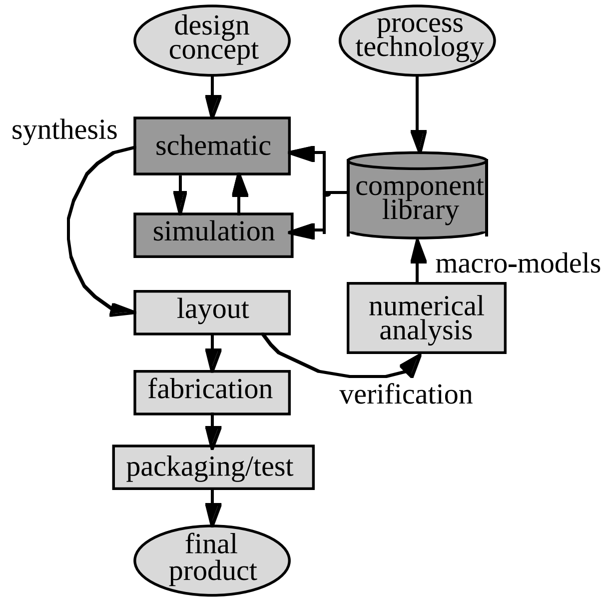

Figure 2. Flowchart of structured MEMS design.

- all, or most, fabrication steps are done externally, so research resources can be invested in design, not standard processing,
- the process is repeatable, so circuit and microstructure designs can be re-used,
- devices improve as the process technology improves (e.g. scaling), and
- prototypes can be reproduced at any time.

Because of their planar ‘2 1/2-D’ topology, surface micromechanics is a MEMS technology which lends itself to abstraction in conventional schematic capture tools. 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 long-term goal is to enable rapid, intuitive exploration and analysis of the design space for complex MEMS.

Schematic Design and Synthesis of MEMS

At Carnegie Mellon, we are developing tools and model libraries to support schematic design and synthesis of MEMS, as shown in Figure 2. Physical and behavioral views of MEMS are currently used by designers, while schematic views have been neglected. The schematic provides a critical link between the physical and behavioral views. The designer is freed from doing detailed layout and 3D numerical simulation in the initial iterative design phase and can explore different design concepts quickly. In the MEMS schematic view, micromechanical devices are designed by assembling iconic representations of microelectromechanical lumped-parameter elements. Reusable elements, such as beam springs, plate masses, electrostatic actuators, and capacitive sensors, are backed by models of varying sophistication. Detailed models with second-order effects are used in simulations while simple first-order models are available for used for automatic optimal component sizing. The designer has freedom to experiment with new micromechanical architectures and then size elements appropriately. The key point is that new devices can be designed and high-level macro-models extracted without layout in the iterative design loop.

Efficient simulation is critical to the iterative design process. Mixed-signal mixed-domain simulation tools will be needed for the schematic design methodology. Many groups are already exploring behavioral MEMS simulation using device macro-models extracted from numerical analysis. Schematic design provides an accelerated method for generating higher-level macro-models, since they are constructed from schematic information and pre-made lumped-element models. Efficient 3D numerical analysis is critically important for generating lumped-element macro-models and for verification of final designs. I will re-emphasize that efforts must be made to link MEMS CAD tools together, including process simulation, numerical analysis, 3D rendering, layout, schematic design, and system simulation.

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