Visual Modeling and Design of Microelectromechanical System (MEMS) Transducers

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ABSTRACT

Microelectromechanical systems (MEMS) integrates miniaturized mechanical structures with electronics to extend the benefits of planar integrated circuit technology to a broader class of systems. To realize the potential and growth of MENS, new modeling, analysis, and design techniques are required to address both mechanics and electronics. The close proximity of the integration of mechanical and electrical domains within the small dimensions associated with very large scale integration (VLSI) presents new energy-coupling issues. The behavior of the overall system is not the simple concatenation of separate mechanical and electrical behaviors, but the simultaneous combination of mechanical and electrical behaviors.

In this paper, we address initial design capture and system conceptualization of microelectromechanical system transducers based on visual modeling and design. We present the concepts of structured topological design, circuit-level branch constitutive differential and algebraic equations (DAEs) characterization, and design-by-direct-manipulation.

Keywords: MEMS, transducers, visual modeling, VHDL-AMS, and design capture.

INTRODUCTION

This paper presents a new design methodology and associated environment for the visual design and modeling of microelectromechanical system (MEMS) transducers. The objective is to define a *circuit* level of abstraction and identify representative artifacts within the level of abstraction that facilitate a unified representation, rendering, and design of microelectromechanical systems. We first discuss the factors motivating the growing interest and use of microelectromechanical systems technology. Next, we discuss specific problems motivating the need for new design capture and conceptualization technology. Then, we present a solution called Visual Integrated-Microelectromechanical VHDL-AMS Interactive Design (VIVID).

Even though there have been notable advances in microelectromechanical systems (MEMS) fabrication technology, MEMS *design* remains a difficult task. Microelectromechanical system design presently involves highly customized analyses that are complicated and often nonrepeatable. There is limited use of hierarchical abstractions; MEMS design and fabrication processes are not readily partitionable and MEMS designers are thus required to be experts in many areas. Hence, there is a need for a more structured design methodology and supporting tool set for microelectromechanical systems (MEMS) that promotes higher levels of abstraction and behavioral design.

Extending MEMS design to higher, *circuit*-oriented levels of abstraction is a major focus of visual modeling. Raising the design level of abstraction for microelectromechanical systems has many benefits. Using a higher level of abstraction oriented at the circuit level enables non-expert MEMS designers to design more complicated systems. Moreover, higher levels of abstraction facilitate the definition of reusable components and the increased use of foundry cell libraries. The level of abstraction of foundry services is consequently raised, along with the efficiency of the design/fabrication interface. A comparable design/fabrication interface was an important and significant factor in establishing very large scale integrated (VLSI) technology.

Use of *analog hardware description languages (VHDL-AMS)* is another major focus of visual modeling, as present microelectromechanical system (MEMS) tools do not leverage the capabilities of analog hardware description languages in a manner comparable to VLSI tools and digital hardware description languages. Coupled-energy behavioral modeling is necessary, as the close proximity and interaction of micromechanical and electrical components introduces domain interactions that substantially complicate system analysis and design.

Visual modeling makes use of visual programming concepts to enhance ease-of-use and design capture efficiency. Visual programming technology seeks to use the powerful medium of graphics to enable effective rendering and direct manipulation of design artifacts, bypassing the bottleneck of typing text. Since hardware description languages and software programming languages are instances of computer languages, is it useful to draw analogies between techniques for facilitating rapid programming and techniques for facilitating rapid modeling; both are attempting to solve similar problems.

The following sections discuss in more detail the principal technical aspects of visual modeling:

- Structured topographical design,
- Visualization and direct manipulation,
- Coupled-energy characterization, and
- VHDL-AMS component modeling.

The paper concludes with summary results and discussion of future work.

STRUCTURED TOPOGRAPHICAL DESIGN

For MEMS visual modeling, the design space must be suitably restricted because visual programming technology presently does not satisfactorily support general-purpose software development [2]. Visual programming has been most successfully applied to domain-specific software development applications where key concepts, characterizations, and renderings can be predefined. In other words, though visual modeling of arbitrary microelectromechanical systems is a desirable goal, it is presently not a feasible goal. Thus, there is a need to restrict the design space by exploiting fabrication cell libraries supporting known topologies.

A semi-custom or structured approach is emphasized in which the design space is explored by systematically examining, sizing, and analyzing a collection of topologies. The structured topological design and modeling approach is key to enabling definition of suitable renderings and manipulations of transduction properties and characterizations.

A structured microelectromechanical system transducer topological design philosophy is similar to the way advanced analog circuits are generally designed, exploiting similarities between microelectromechanical system (MEMS) and analog microelectronics design; both are continuous time systems. For example, Figure 1 illustrates a hierarchical structure for analog microelectronic systems [5]. Design is the process of exploring various known topologies (designs) for each of the sub-circuits and then composing the sub-circuits into the desired overall circuit design.

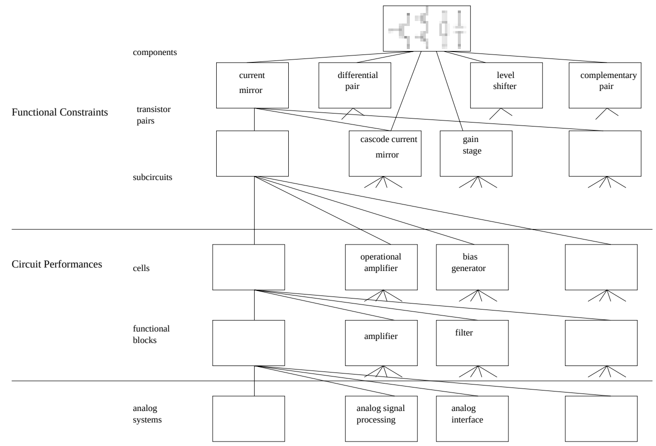

Figure 1: Hierarchical Structure of Analog Microelectronic Systems

VIVID uses the Microelectronics Center of North Carolina (MCNC) Consolidated Micromechanical Element Library (CaMEL) as a sample foundry cell library. Using known topologies, microelectromechanical transducers can be designed by visually exploring candidate topologies, analyzing possible sizings, and determining the particular topology/sizing that best satisfies design specifications.

VISUALIZATION AND DIRECT MANIPULATION

Visualization and direct manipulation combine to form the basic user interface and interaction paradigm behind visual modeling. Visualization exploits the increasing capabilities and decreasing costs of computer-based graphics to generate renderings of domain-specific abstractions as the primary medium of user/tool interaction. Direct manipulation refers to the concept that the renderings are directly manipulated, in a controlled manner, by the designer as a way to convey design intent, minimizing text entry. Allowed manipulations are presented using visual clues to assist a MEMS designer in designing a transducer.

More specifically, visual microelectromechanical transducer modeling emphasizes design details relevant to the *circuit* level of abstraction. A MEMS transducer is conceptualized as a time varying electrical device, having properties a function of one or more environmental operands. The designer is concerned with nominal (target) values of the electrical device, such as capacitance or resistance, and how the electromechanical coupling causes changes in the nominal values. Renderings and characterizations of transducers are designed to be both intuitive and consistent with an associated circuit simulation capability [3]. For example, the rendering of a linear combdrive resonator is shown in Figure 2; details of fabrication layers are not rendered. Direct manipulation cues of the capacitive transducer are provided by the small rectangles. Transducer topologies and as-

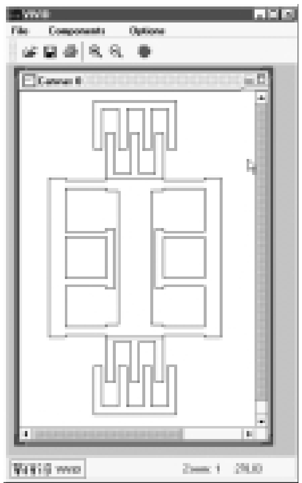

Figure 2: Linear Combdrive Resonator Rendering

sociated characterizations are presented in a way that makes sense to the *circuit* designer. Design is focused on circuit-level transduction properties, not underlying physical implementations.

COUPLED-ENERGY CHARACTERIZATION

Visual modeling unifies the mathematical characterization and analysis of electrical and mechanical systems by exploiting the fact that the dynamical behavior of both physical systems can be represented by a system of simultaneous differential and algebraic equations (DAEs). Differential and algebraic equations form a powerful and general mathematical framework for describing many aspects of nature, with electrical circuits and motion of suspended mechanical structures being just two examples [1].

Microelectromechanical differential and algebraic equations are generated within a systematic framework recognizing linear independence and energy conservation. The global structure of the equations is based on circuit network topology. Equations governing the behavior of the network branches - devices - are defined by *branch constitutive relations.* Branch constitutive equations define the relationships between the *across* and *through* quantities, which for the electrical energy domain are respectively applied potential gradient (voltage) and the resulting time derivative of state (current).

Thus, from a formal mathematical perspective, visual modeling focuses on the task of helping the designer define branch constitutive relationships for the particular microelectromechanical transducer. As an example, consider a piezoresistive microelectromechanical transducer. Piezoresistive transducers translate an environmental measurand involving force to a change in electrical resistance. The branch constitutive relationships for a basic piezoresistive microelectromechanical transducer are summarized below [6], [7]. Equations 1, 2, 3, and 4 collectively describe the relation between an applied force and the resulting change in resistance and, thus, define the branch constitutive relations for an isotropic piezoresistive transducer.

$$\frac{dR}{R} = K\,\epsilon \approx \frac{\Delta R}{R} \tag{1}$$

$$K = \frac{\frac{dR}{R}}{\frac{dL}{L}} = \frac{\frac{d\rho}{\rho}}{\frac{dL}{L}} + 1 + 2\mu \tag{2}$$

$$\sigma = E\epsilon \tag{3}$$

$$\sigma = \frac{F}{A} \tag{4}$$

R - resistance	ρ - resistivity
L - length	μ - Poisson's ratio
K - gauge factor	ϵ - strain
σ - stress	E - Young's modulus
F - transverse force	A - cross-sectional area

VHDL-AMS Component Modeling

To document the resulting microelectromechanical system transducer design, a component model is generated in the analog hardware description language VHDL-AMS.[1] This component model drives subsequent design activities, such as circuit-level simulation.

VHDL-AMS denotes the portion of the hardware description language VHDL that addresses describing continuous time systems having behavior governed by a set of simultaneous equations. The equations are differential and algebraic equations (DAEs) and the unknowns are continuous, analytic functions of time. The solution of the set of simultaneous equations over a period of time is obtained by repeatedly invoking an "analog solver" and the results yield the continuous waveforms of the unknowns. The suffix "AMS" is an acronym for "analog and mixed signal". Simultaneous differential and algebraic equations (DAEs) provide a general mathematical framework capable of describing many types of analog systems, electrical being just one example. This generality is the motivation, in part, for the terminology "mixed-signal".

[1] VHDL-AMS is a standard sponsored by the Institute for Electrical and Electronic Engineers (IEEE), denoted by 1076.1.

Microelectromechanical system models developed via visual modeling define a conservative system of simultaneous differential and algebraic equations (DAEs). Based on the branch constitutive relations derived for a piezoresistive microelectromechanical transducer given in the previous section, a sample VHDL-AMS component model is given in Figure 3. The composite system modeling

```
use IEEE.ELECTRICAL_SYSTEMS.all;
use IEEE.MECHANICAL_SYSTEMS.all;
entity MEMS_PIEZORES_TRANSDUCER is
 generic (constant R_NOM         : RESISTANCE;
          constant YOUNG_MOD     : REAL;
          constant POISSON_RATIO : REAL;
          constant APPLIED_AREA  : AREA);

 port    (terminal NODE1, NODE2 : ELECTRICAL;
          quantity F : in FORCE);
end entity MEMS_PIEZORES_TRANSDUCER;

architecture BEHAVIORAL of
                 MEMS_PIEZORES_TRANSDUCER is
 quantity V across I through NODE1 to NODE2;
 quantity R, R_DELTA : REAL;
 quantity E_STRAIN, K, STRESS : REAL;

begin
 -- define branch constitutive equations
 -- conservative energy network relations
  V == R * I;

 -- adjoint energy network relations
  R == R_NOM * (1.0 + R_DELTA);
  R_DELTA == K * E_STRAIN;
  E_STRAIN == STRESS/YOUNG_MOD;
  K == 1.0 + 2.0*POISSON_RATIO;
  STRESS == F/APPLIED_AREA;
end architecture BEHAVIORAL;
```

Figure 3: VHDL-AMS Component Model of Piezoresistive Microelectromechanical Transducer

style is discussed in more detail in [4].

SUMMARY

We have presented a new design approach for microelectromechanical systems based on visual modeling and structured topological analysis using direct manipulation. A structured design methodology for microelectromechanical systems emphasizes the use of cell libraries. Full custom design is constrained by using known topologies and investigating a variety of combinations of design parameters to modifying/configure the topologies to conform to desired specifications. Changes are analyzed and checked by internal compositional rules to ensure compliance with foundry-specific design rules.

A circuit perspective of the microelectromechanical transducer is rendered; only the design data relevant to key transducer characterizations is highlighted and details associated with secondary considerations are hidden. Transduction properties are rendered and can be sized in an intuitive way. A coupled-energy characterization is proposed supporting circuit level branch constitutive relations defined as differential and algebraic equations (DAEs). Circuit simulation technology is leveraged to formulate the equations using an overall framework reflective of the fundamental physical laws of conservation of energy and the specifics of branch constitutive relationships. Examples are presented of piezoresistive and capacitive microelectromechanical system transducer modeling and design.

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