Design Automation of MEMS Systems Using Behavioral Modeling

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Abstract

We propose a behavioral approach to designing MEMS devices. This approach differs from much current research in that this approach would not require dimensional parameters for the device, but instead would require a high level, functional or behavioral description. This paper examines how such an approach would work using a case study of an optical processor manually designed using the MUMPs process. Keywords: MEMS, CAD for MEMS, behavioral modeling, design automation.

1. Introduction

To aid the growth in MEMS research and development, techniques for high-level design of these systems are needed. Using these methods and available manufacturing processes, the high-level designer should be able to design, simulate, and fabricate complicated devices and systems without concern for the low-level details (i.e., mask level descriptions) of a design. Today's available VLSI CAD tools can do low-level circuit synthesis from abstract models at a higher level (for example, VHDL [2]), and rapid simulation of the circuit's performance. However, the design of MEMS systems does not parallel this at all. Usually a MEMS system design is broken into two separate steps: hand layout and manual modeling and simulation of the system. This is quite time consuming. Analogous to the VLSI world in which transistor sizing may be automated through different programs, design of cells for MEMS devices should be automated with the use of programs. These programs should calculate dimensions from a specified behavior. In addition, as VLSI designers are using higher level tools which remove them from worrying about adding "plugs" to a design to prevent latchup, MEMS designers should be using higher level tools which remove them from worrying about process dependent variables and low level problems which the tools should handle.

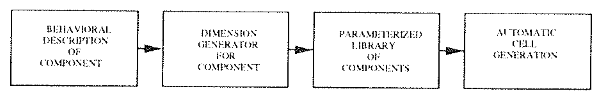

Figure 1. Design Automation Process

If there is to be automation for the design of MEMS systems, there must be a separation between the designer and the low-level design of components. So, it is imperative that there exist a set of primitive devices which have parameters (such as dimensions and specifications of behavior) from which the high-level designer may choose. The designer should be able to automatically generate these devices from a behavioral description into "cells" for a layout design. Thus, the designer is enabled to create the layout of the circuit geometry at a higher, more abstract level. In addition, by using these parameterized components, which have been tested for performance, the high-level designer will have added confidence in the final performance of the system. [Figure 1].

In order to create this set of primitive MEMS devices, it is necessary to create models for each primitive device. One way currently being explored [6] to create a parameterized device is to create a mathe-

*Supported by the University of Cincinnati Fellowhip, The University of Cincinnati Research Challenge Grant and the United States Air Force, contract no. F33615-96-2-1945.

†Supported The University of Cincinnati Research Challenge Grant and the United States Air Force, contract no. F33615-96-2-1945.

0-7695-0104-4/99 $10.00 © 1999 IEEE

matical model for the device. The user can enter the dimensions of the device. At this point, the model may be simulated. The user can change the parameters until the desired result is attained. Such parameterized libraries are being created by Tanner [9], and by MCNC [6]. For instance, MCNC maintains the Consolidated Micromechanical Element Library, CaMEL. The library consists of two independent parts; the non-parameterized cell database and the parameterized microelectromechanical element library, PME. Their objective is to provide MEMS cell libraries that are useful not only to novice MEMS designers, but to experienced ones as well. Both libraries are intended to assist the user in the design and layout of MEMS devices by providing an initial layout for components of a MEMS system. It is assumed that the user will modify these elements and customize them as desired and assemble designs using a suitable mask layout editor. However, we concede that this is still an iterative process which would be very time consuming.

Another more interesting way is our proposal to allow the user to enter the device by behavioral modeling. In this method the user would choose a component from a library of parts, and specify a behavior, such as maximum area the device may use and the voltage range at which the device must operate to obtain the desired result. In this case the mask layout of the component should be automated and the high-level designer should only be provided the layout cell that meets the specified constraints.

We illustrate our approach by a case study of an actual MEMS system designed and constructed at the University of Cincinnati. This paper will address some of the problems encountered with the current state of MEMS system design, suggested solutions to some of these problems, and what was actually achieved. The design of one MEMS primitive, a micro-mirror, which was used in the system, is used as an example of how the process of automating MEMS design may be accomplished. We now begin our discussion of the application of the micro-mirror.

2. Basics of micro-mirror

The micro-mirror device that we are considering is basically a cantilever beam with a rectangular plate connected to the end of the beam [Figure 2]. In addition, directly beneath the plate is another plate, which is electrically isolated from the upper plate. This lower plate is used as a drive for the upper one. When a voltage is applied between the two plates, they act as a parallel plate capacitor. Thus, when a voltage is applied deflection of the beam occurs due to the force of

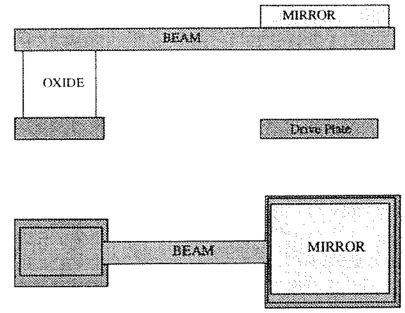

Figure 2. Structure of Micro-Mirror

attraction between the two plates. This voltage can be used to actuate the mirror. We can measure the deflection of the beam for any voltage, but we are especially interested in the case of the "pull-in" voltage, the voltage at which the plates are brought together, or to a stopper which keeps the two plates from touching [4]. At pull-in and higher voltages the mirror would be considered in the down position. The mirror can be returned to the up position by reducing the voltage. Therefore, the mirror could be controlled with an input voltage to oscillate between the up and down positions. In this case the mirror could be used as a "light switch" to send optical signals to a receiver.

3. Concentration of the research

Our research concentrates on design automation of the micro-mirror. The actual construction of the micro-mirror was done manually using AUTOCAD as a layout mask editor and drawn by hand. Many micro-mirrors were used in the system and many additional mirrors were included only for testing purposes. In addition, some of the mirrors incorporated a unique technique of "corrugating" the beam in an effort to reduce the actuation voltage of the micro-mirror. These micro-mirrors were of varying dimensions, and thus took a great deal of time and effort to construct. In addition, because the design was custom built, problems in the design were not detected until after the system had been fabricated and tested. It is believed that such a system could have been constructed in less time and avoided the design problems, if a design system for automating the design had been used.

4. Method for design automation

Four things are necessary for the automation of MEMS system design:

1) A well-developed library of parameterized components needs to exist.

2) Using this library, each component needs to have a mathematical model which describes the behavior of the component given specific dimensions for the component.

3) Algorithms are needed to generate the correct dimensions of the component which will meet the behavioral specification given.

4) From the dimensions calculated, a cell needs to be automatically generated by inserting the calculated dimensions into the parameterized library component.

It must be noted that these four steps are process dependent. This research bases its work from MCNC's MUMPS process [1]. Even though problems with the MUMPS process were encountered, it can still be used to discover what types of behavior can be handled automatically by the design tools.

Currently, the library of parameterized components contains only the design for the micro-mirror. MATHEMATICA [12] was utilized to simulate the behavioral equations for the micro-mirror. This model enabled dimensions of a micro-mirror to be entered, and returned the deflection of the mirror for a given voltage. A program was written in MATHEMATICA implementing an incremental algorithm which adjusted the dimensions of the micro-mirror until the specified behavior was met. In this case, it was when the mirror deflected into the down position at a specified actuation voltage. This program could be enhanced if a binary search algorithm replaced the incremental algorithm. Once the dimensions were calculated for such a micro-mirror, the dimensions were used to create a layout mask file (CIF) of the micro-mirror. At this point, the micro-mirror layout mask file may be input into a layout editor such as L-EDIT [10], which does accept CIF [7] format.

5. Simulation using simple models

Many applications that use cantilever beams (such as the micro-mirror) can be quite complex in their structure. In addition, many of the simulators available tend to be very computationally intense. In other words, when a simulation is done, there is a great deal of overhead in the computation. In the case of the micro-mirror generation, the simulation of the device may require a vast number of runs with varying dimensions. It is plausible to sufficiently decrease the amount of overhead in these computations, while still obtaining reasonable results. The method of doing this was

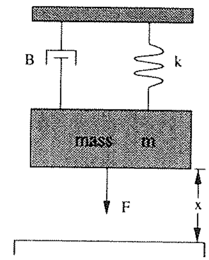

Figure 3. Dampened Spring Mass System

to make simplifying assumptions about the problem, and to only concentrate on the most critical design parameters. The two most critical behavioral parameters for the application of the micro- mirror being discussed are:

1) Actuation Voltage

2) Slope of the mirror

Our model concentrated on generating a mirror with the dimensions necessary to actuate at a given voltage.

The model used for the micro-mirror was developed using the cantilever beam as its main focus. The problem was reduced to the deflection at the end of a cantilever beam at its free end given a force applied to the free end. The force at the end of the beam was calculated by modeling the force as the attractive force of capacitance between two parallel plates. The equation for the attractive force is given as:

$$F = \frac{AE_0V^2}{2x^2}$$

where F is the attractive force, A is the area of the mirror, V is the voltage,and x is the distance between the two plates. However, one more simplification in the model was made. Given small deflections of a cantilever beam, the deflection at the end of the beam can be approximated by modeling the cantilever beam as a dampened spring-mass system [8] [Figure 3]. By doing so, the equations that need to be solved are reduced from second order partial differential equation [11] to a second order ordinary differential equation [8] which is given as the following:

$$F = Mx'' + Bx' + kx$$

where F is the force applied to the mass, M is the mass, B is the dampening coefficient, and k is the spring constant.

6. Results

Our behavioral model for the cantilever beam modeled as a dampened spring-mass system were com-

Micro Mirror Results		
	Actual Dimensions micrometers	Predicted Dimensions micrometers
Mirror Length	70	59
Mirror Width	70	59
Beam Length	30	30
Beam Width	30	30
Pull in Voltage (V)	22.5	--
Behavioral predicted pull in voltage (V)	30.0	22.5

Figure 4. Actual Vs. Predicted Behavior

pared using various simulators on multiple dimensioned beams. The deflection that the behavioral model compared well with that given by simulators such as ANSYS [3], and MECHANICS EXPLORER [5]. Given the added confidence that the model worked with the classical mechanical results, the results were compared with an actual fabricated micro-mirror. The results for this mirror are recorded in figure 4. Our model predicted that the actuating voltage for a mirror with the given dimensions would be 30 volts. However, the actual voltage for pull-in on the beam occurred at 22.5 volts. The mirrors in the system are currently undergoing testing, and at this point results for the other fabricated mirrors are not available. The fabricated mirror for which the results were available may not give an accurate picture of the behavioral model's prediction due to the fact that it was one of the special beams which incorporated the "corrugation" that was mentioned previously. We are currently investigating how to account for the corrugation both in the MATHEMATICA model and in the standard mechanical simulators. However, it stands to reason that the actual pull-in voltage would be lower than the predicted voltage in this case, since that is the reason for the corrugation in the beam. What can be gleaned from this example is that the voltage is at least in the correct range. Figure 4 also gives the dimensions of the mirror that have a predicted pull-in voltage at 22.5 volts.

Problems in the testing of many of the mirrors occurred. Many of the mirrors once actuated, would not release due to a "sticking" effect with the oxide layer. However, the MUMPS process can be altered to avoid this problem. In addition, measuring the slope of the mirror was problematic in that the layers were not flat enough to get good measurements.

7. Conclusions

Since insufficient measurements have been gathered, it is not clear whether the behavioral model for the micro-mirror is adequate for the parameters being determined. If it turns out that the model is inadequate, then certain simplifying assumptions must be eliminated from the model. However, it is clear that, even with an overly simplified model of the problem, the results are in the correct range.

Once adequate behavioral models and parameterized component libraries are developed, MEMS design can be taken to a higher level of abstraction. The designer can be removed from the low level mask descriptions and deal with components as in VLSI design. In addition, issues such as the problem of "sticking" should be handled by the design tools automatically, and not involve the designer. Thus, once such a paradigm for MEMS design is accepted, a system, such as the optical processor in this case study, could be designed at a higher level of abstraction, and the problems that were encountered could have been eliminated by the design tools.

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