Structured Design Methods for MEMS

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While considerable progress has been made in the areas of etch simulation [4, 6, 7, 8, 18], finite element analysis [3, 5, 11, 14, 16, 17, 22], corner compensation [1, 13, 15], and design [10, 19, 20, 21] the fabrication of MEMS has been made without the benefit of design automation techniques. In contrast, the design of VLSI systems has become highly formalized and automated. One of the goals of Mead and Conway's early work in the VLSI area was to permit "ordinary engineers" to perform design [12]. Prior to their work, VLSI design was the exclusive domain of highly trained and experienced specialists. Other engineering domains (e.g., MEMS design) have not had the benefit of the same level of formalism and automation in design, and engineering design in these areas remains the province of highly trained and experienced specialists.[1]

Work recently begun in several research groups (including our own) aims to permit rapid, accurate, conservative mask-layout synthesis of MEMS in a way analogous to present-day VLSI design. The long-range objective is to enable a MEMS designer to specify a desired micro-mechanical function (e.g., a mechanical spring with particular characteristics), and have a system automatically generate the information (mask-layout, and other fabrication instructions) to create the shape that exhibits the desired function. This approach will mean that MEMS designers will be able to concentrate on the desired function of the device, rather than the details of its physical manifestation.

Thus the goal is:

- To develop a MEMS mask-layout <u>synthesis</u> methodology
  that will automatically create a mask-layout
  for a given desired final 3-D shape.

Attaining this goal will, however, be difficult. Mechanical systems are more complex than digital VLSI: there is no (single) language to describe mechanical function; the geometry of mechanical systems is typically complex (non-Manhattan); the number of primitive mechanical elements is large; there is no separation between function and form (the case of a mechanical transmission, for example, supports the bearings; contains the

[1] Here the term "formal" is used to mean computable, in the sense that a design process can be automated. There are many methods that are in daily use in mechanical engineering design, but are insufficiently formal to permit automation of the design process. "Systematized" is a commonly used synonym to "formal" as the term is used here.

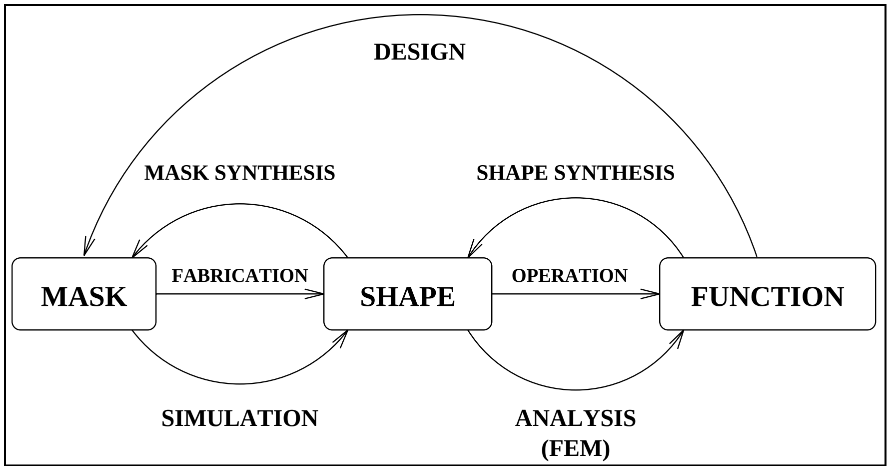

Figure 1: Simulation vs. Synthesis, Design vs. Analysis

lubricant; provides the mounting; provides cooling; etc.). However, for suitably constrained mechanical domains (perhaps 2.5D multi-layer surface micromachining) some progress may be made. It is important to observe that while design automation for digital VLSI has achieved considerable success, this is not the same a general electrical or electronic design. Many areas of analog or microwave (etc.) electronics design remains largely unautomated. Similarly, structured mechanical design methods will most certainly be developed for constrained (perhaps narrow) systems and applications.

The primary method for creating a MEMS mask-layout today is trial-and-error, guided by experience. Consequently, many iterations, and hence many prototypes, are typically required to develop a mask-layout that results in the desired shape and desired function. As Brysek, Petersen, and McCulley recently observed (1994):

> "In-depth knowledge of the [fabrication] process is needed because in micromachining 'what you see' is often NOT 'what you get'." [2, Page 25]

An illustration of this point is shown in Figure 2. This will be particularly true for future MEMS systems which will involve many degrees of freedom and/or complicated 3-dimensional shapes.

Because of the geometric complexity of surface fabricated MEMS devices, the present MEMS design procedure can be characterized as a *mask-to-shape-to-function* process. Even though the designer may start with a function and shape in mind, the complexity of the fabrication process forces the design cycle to iterate around the mask-to-shape-to-function evaluation process, as shown by the bottom arrows in Figure 1. However, the desired approach is exactly the reverse: *function-to-shape-to-mask*. That is, the designer conceives of a MEMS function, then through an automated (but perhaps iterative) process determines a shape that will exhibit the desired function, as shown by the top arrows in Figure 1. For example, the designer can develop a tentative shape, and then use

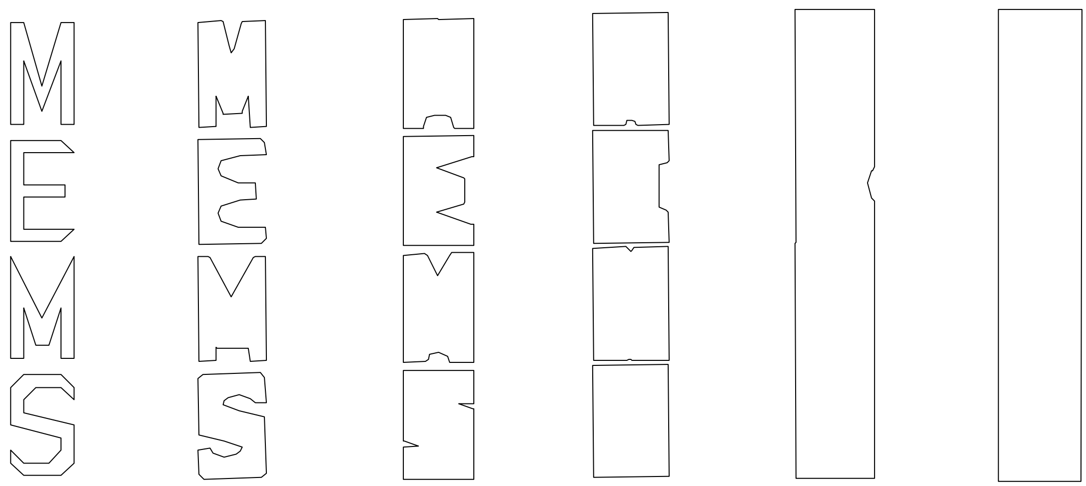

Figure 2: Input mask shape (on the left) and changing shape with time; anisotropic etchant simulation.

FEA methods to iteratively refine the shape until it exhibits the desired characteristics. Next, using an automated (but again perhaps iterative) process, the shape description is used to determine a mask-layout and a set of fabrication instructions that will create the desired shape, or the best possible approximation to that shape. In the case that the desired shape can not be fabricated, the designer may again need to use FEA tools to evaluate the suitability of the best approximate shape. For this reason, a standard communication format for the transfer of information between different levels of MEMS design is proposed.

Current FEA (and related MEMS CAD) approaches should be augmented to include the complexities of typical MEMS fabrication processes into the design cycle. Current MEMS FEA methods focus on the relationship between function and (3-D) shape. Additionally the relationship between (3-D) shape and mask-layout should be further formalized.

To develop formal and computable methods for the "shape-to-mask" process, a more exact computational model of the MEMS fabrication process is required. Such models will form the basis for the *forward* or *simulation* problem. That is, the solution to the forward problem determines what shape results from a given mask and a given etching process. More importantly, the model for the forward process is necessarily the basis for the *inverse* or *mask-layout synthesis* problem–i.e., determine the mask shape that yields a desired processed shape for a given etchant. One result that can commonly occur, is that no such mask shape exists. In this case, a *shape approximation metric* will need to be applied to determine the closest shape (or perhaps the closest function).

A closely related problem is that of the optimally "robust" shape. Even if a desired shape can be produced by an idealized fabrication process, deviations in the processed shape from the desired shape will occur due to process variations, small errors in mask alignment, errors in etch rate diagram data, non-ideal effects, and finite mask resolution.

One might alternatively define a *robustness metric* or a *sensitivity metric* for a shape. That is, how likely it is that the desired shape will be obtained (or obtained within an acceptable tolerance), assuming an expected range of processing errors? Analogously, how sensitive is a given shape to processing variations? Such metrics are useful for many applications. In the case that more than one mask shape will lead to the same processed shape under ideal conditions, the robustness metric could be used to select the most robust mask shape. The robustness metric can also be used to compare the output of different design procedures. Robust metrics may also be the basis for procedures that estimate process yields.

As the complexity of MEMS grows, the need for design automation will also grow. Design automation for MEMS represents a significant opportunity to build on the pioneering work in MEMS fabrication, modeling and analysis, along with the established work in VLSI design automation. The added complexity of 2- and 3-D mechanical devices introduce new challenges and will require considerable extensions beyond the VLSI domain. However, the inherent limitations (limited number of materials, limited shapes and sizes, limited forces, etc.) hold the promise for producing more tangible design automation results than have been obtained in the macro-mechanical domain.

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