MEMS/NEMS Design Automation and Synthesis

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Project Description: The goal of the project is to extend the existing SUGAR MEMS simulator into a design synthesis tool that supports the early stages of MEMS/NEMS conceptual design. We are developing a broad base of MEMS building blocks and hierarchies of clusters and assemblies that can be integrated into a "MEMS/NEMS Design Automation and Synthesis" framework for constructing a large range of MEMS suspension devices.

1. Project Tasks for Year 2

- Develop a preliminary indexed module library within Sugar that includes the building blocks found in Year 1.
- Re-synthesize some of the most representative MEMS design examples from the literature and verify adequacy of module library.
- Develop a human-interactive framework around our exploratory GA algorithms to manually identify promising patterns in the designs generated by stochastic evolutionary algorithms and to guide the future direction of the exploratory search.
- Identify dominant clusters of primitives that appear frequently in the SUGAR net lists and formalize them as parameterized cluster modules that can then be used in the synthesis runs with higher effectiveness.
- Fabricate, test, evaluate, and feed back any lessons learned.

Activities and Findings

We completed all of the Year 1 tasks and are on target for completing all of our Year 2 tasks by June 2005. The Year 2 activities and findings are summarized below.

A global stochastic optimization approach – the Multi-Objective Genetic Algorithm (MOGA) – has proved to be a suitable method for MEMS design synthesis. To develop a flexible MEMS design automation tool, an object-oriented hierarchical MEMS synthesis framework was developed, which integrates an object-oriented component library with the MEMS simulation tool called *Sugar* (an open source simulation tool for MEMS devices based on nodal analysis techniques) at two levels of optimization: global genetic algorithms and local gradient-based refinement [1,3]. An object-oriented data structure is used to represent hierarchical levels of elements in the design library and their connectivity. Additionally, all elements encapsulate instructions and restrictions for the genetic operations of mutation and crossover. The parameterized component library includes distinct low-level primitive elements and high-level clusters of primitive elements [15]. In our case-based framework, the component library, including fabrication and simulation constraints, are updated as new designs are tested and evaluated (see Figure 1).

During the past year we developed and tested a human-interactive framework around GA algorithms called MEMS-Interactive-Evolutionary Computation (MEMS-IEC). It gives a human designer an option to select and further evolve designs generated by our existing stochastic techniques. It allows a user to include human judgment and design experience as an integral part of the simulation software's assessment of designs performance, thus addressing design factors that are hard to simulate with modified nodal analyses, such as stress concentrations and dynamic interference [2]. The IEC approach for MEMS Design synthesis is currently under review for a patent application [18].

A starting base of existing MEMS designs has been identified from the literature and indexed into a preliminary MEMS module library [8,14]. These designs have been broken down into basic elements and clusters in parameterized form. The SUGAR net lists for object-oriented building blocks have been created and will be released in the next year with the next update of the SUGAR software. We will make new building blocks in SUGAR freely available through source code, documentation, as well as a web service.

In analyzing clusters and patterns of features from published MEMS designs, we identified the need to develop a curved beam element. The curved beam is needed to effectively develop clusters like spiral springs and circular rings. The two-node six-degree of freedom element being developed takes the effects of flexural, axial and shear deformation into account using a hybrid-mixed formulation based on the Hellinger-Reissner variational principle. The accuracy of the method is being verified with standard test problems and exact solutions from the theory of elasticity. Further testing of the numerical results will be compared with those obtained from finite element analyses. To date, the curved beam element in these calculations shows very good convergence results. After testing and validation, the curved beam formulation will be added to the indexed element and case database. [16]

A wide range of MOGA-generated MEMS resonating masses have been fabricated and characterized to validate our use of SUGAR as an effective evaluation engine, and to better understand the constraints and objectives necessary for accurate synthesis. A test-feedback strategy was developed for improving evolutionary synthesis based on the results from the fabrication and characterization of output from our GA-based synthesis program. Simulator and fabrication conditions lead to certain configurations of output differing significantly from predicted performance when fabricated and measured. Using lessons learned from a MEMS synthesis characterization study, four modifications to the objectives and constraint settings of the GA formulation are evaluated to produce results that more closely match desired performance when fabricated. Through the characterization, we have been able to classify the results into three groups: 1) designs where the measured performance matches the simulation accurately; 2) designs where the simulation differs from measured data due to simulator limitations, and 3) designs where the simulations differ from measured data due to fabrication variations. By studying these groups, we were able to identify deficiencies in our current synthesis encoding and suggest additional constraints or objectives that will lead to better designs in the future. To date, statistical tests show improvement in the quality of the GA's output, producing designs with significantly less simulation and fabrication errors using the proposed methods. [3,17].

Eighteen publications reflecting the research partially supported by this grant are listed below. This list includes two completed MS theses [14,15] and one PhD dissertation [17] completed in the last year. Another MS thesis/project is expected to be completed by the end of the Spring 2005 semester [16].

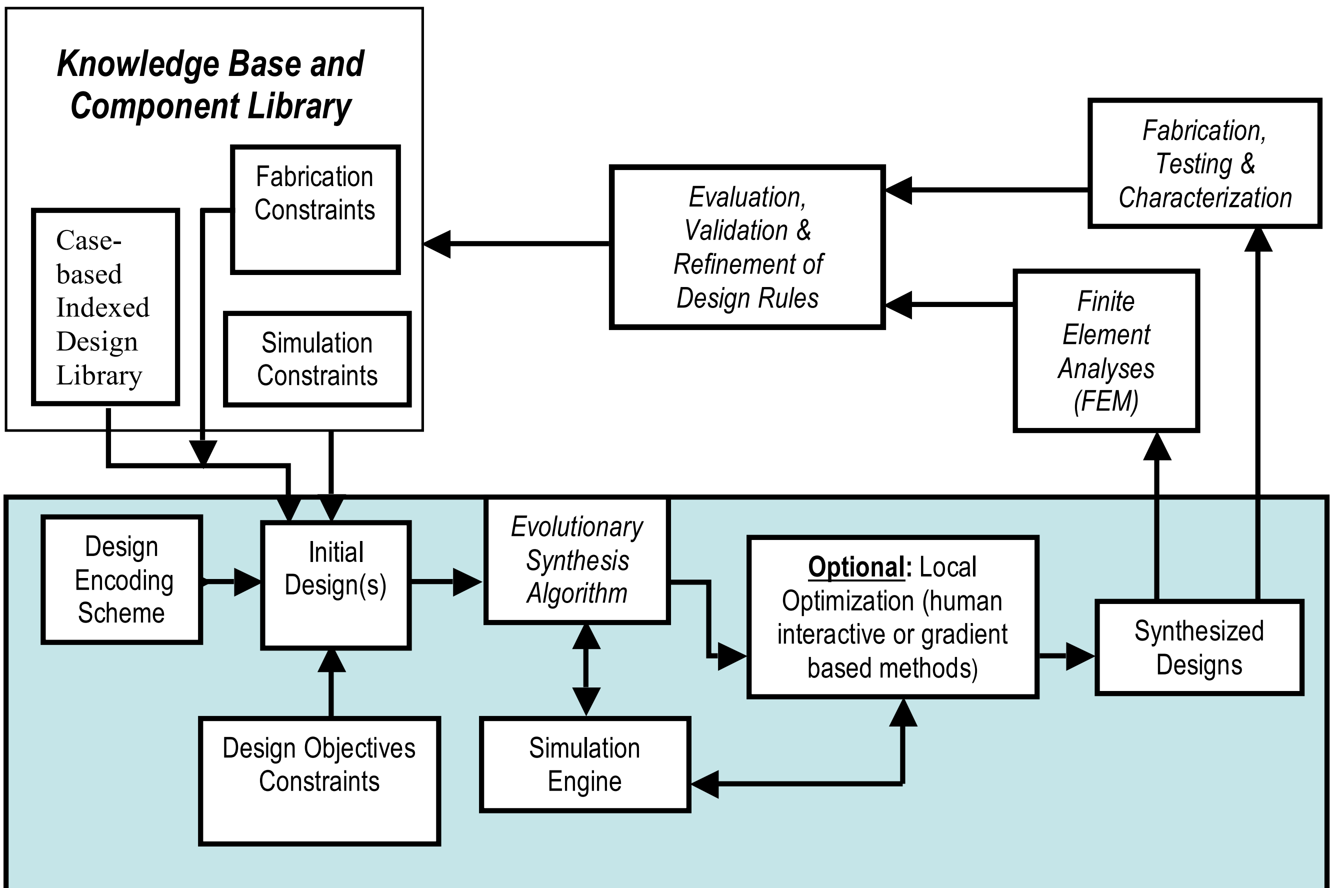

Figure 1: Design Synthesis Module

2. Training and Development

The grant has supported a weekly interdisciplinary MEMS/NEMS CAD seminar with approximately 15 graduate students and 5 faculty.

3. Outreach Activities

As this research is conducted through the Berkeley Sensors and Actuator Center (BSAC), bi-annual reports, posters and presentations have also been provided to the industrial community [5-13].

4. Contributions within Discipline

The main focus of the grant is in electrical and mechanical engineering as well as computer science.

5. Contributions to Other Disciplines

Contributions to evolutionary algorithms for computer-aided design.

6. Contributions to Human Resource Development

Support for 6 graduate students.

7. Contributions to Resources for Research and Education

Examples of MEMS cases have been added to the NEEDS digital library of educational resources at www.needs.org (search over the series – MEMS Design Cases).

8. Contributions Beyond Science and Engineering

None yet.

9. Publications and Presentations (to date)

Journals

None yet.

Conference Proceedings

1. Kamalian, R., A.M. Agogino and H. Takagi, "The Role Of Constraints and Human Interaction in Evolving MEMS Designs: Microresonator Case Study," *Proceedings of DETC'04, ASME 2004 Design Engineering Technical Conference*, Design Automation track, Paper # DETC2004-57462, CD ROM, ISBN # I710CD.
2. Kamalian, R., H. Takagi, and A.M. Agogino, "Optimized Design of MEMS by Evolutionary Multi-objective Optimization with Interactive Evolutionary Computation," Proceedings of the GECCO 2004 (Genetic and Evolutionary Computation Conference; June 26-30, 2004, Seattle, Washington), ISBN # is 3-540-22343-6, Vol. 2, pp. 1030-1041, 2004.
3. Zhang, Y., R. Kamalian, A.M. Agogino and C.H. Séquin, "Hierarchical MEMS Synthesis and Optimization," SPIE Conference on Smart Structures and Materials, Paper No. 5763-12, March 7-10, 2005, San Diego CA.

4. Kamalian, R. and A.M. Agogino, "Improving Evolutionary MEMS Synthesis through Fabrication and Testing Feedback", submitted to IEEE SMC2005. (under review)

Reports

5. Kamalian, Raffi, Alice M. Agogino, James Demmel, “MEMS Synthesis Using Stochastic Optimization”, (Berkeley Sensor and Actuator Center Researchers’ Industrial Advisory Board, September 2003).
6. Kamalian, Raffi, Alice M. Agogino, James Demmel, “MEMS Synthesis Using Stochastic Optimization”, (Berkeley Sensor and Actuator Center Researchers’ Industrial Advisory Board, March 2004).
7. Kamalian, Raffi, Ying Zhang, Alice M. Agogino, James Demmel, “MEMS Synthesis Using Stochastic Optimization” (Berkeley Sensor and Actuator Center Researchers’ Industrial Advisory Board, September 2004).
8. Cobb, Corie, Ying Zhang, Alice M. Agogino, Carlo H. Séquin and K. Pister, "MEMS Design Synthesis and Optimization", (Berkeley Sensor and Actuator Center Researchers’ Industrial Advisory Board, March 2005).

Presentations

9. Kamalian, Raffi , Poster, “MEMS Synthesis Using Stochastic Optimization”, (Berkeley Sensor and Actuator Center Researchers’ Industrial Advisory Board, September 2003).
10. Kamalian, Raffi , Poster, “MEMS Synthesis Using Stochastic Optimization”, (Berkeley Sensor and Actuator Center Researchers’ Industrial Advisory Board, March 2004).
11. Kamalian, Raffi, Technical Presentation “MEMS Simulation and Synthesis: Sensors & RF Applications II: Automated Synthesis of MEMS”, (Berkeley Sensor and Actuator Center Researchers’ Industrial Advisory Board, September 2004).
12. Kamalian, Raffi, Poster, “MEMS Synthesis Using Stochastic Optimization”, (Berkeley Sensor and Actuator Center Researchers’ Industrial Advisory Board, September 2004).
13. Cobb, Corie, Poster, “MEMS Design Synthesis and Optimization”, (Berkeley Sensor and Actuator Center Researchers’ Industrial Advisory Board, March 2005).

MS Theses/Reports

14. Zarif, M.R., "Categorization of Current MEMS Suspension Design Variants," MS Plan II report, Spring 2004, Department of Mechanical Engineering, University of California at Berkeley.
15. Graf, S., “GA Building Blocks and Data Structures for MEMS/NEMS Design Automation and Synthesis,” Diploma Thesis, Department of Computer Science,

RWTH Aachen (in cooperation with the Department of Mechanical Engineering, University of California, Berkeley), Oct. 2004.

16. Ranganathan, V., "Locking-free Curved Beam Finite Element Formulation for MEMS Synthesis", Spring 2005, Department of Mechanical Engineering, University of California at Berkeley (expected April, 2005).

PhD Dissertations

17. Kamalian, R., "Evolutionary Synthesis of MEMS Devices," Doctoral Dissertation, Fall 2004, Department of Mechanical Engineering, University of California at Berkeley.

Patents

18. A.M. Agogino, R. Kamalian, and H. Takagi, *Engineering Design System Using Human Interactive Evaluation*, U.C. Case No. B05-029-1, Attorney Docket No. 010030-000600US. (under review).