Evolutionary Design Optimization of MEMS: A Brief Review

Haoshen Zhu, Pan Wang
Wuhan University of Technology
zhuhaosheng@vip.sina.com, jfpwang@yeah.net

Zhun Fan
Technical University of Denmark
zhfa@man.dtu.dk

***Abstract*-** **The limitations of the conventional automated design tools for Micro-Electro-Mechanical-Systems (MEMS) design optimization (DO) are discussed in this paper. In order to overcome these difficulties, a recent trend in DO of MEMS is inspired by the natural evolution mechanism. Various techniques, especially the evolutionary computation (EC), have been adopted for the DO of MEMS. This paper presents a review of the achievements in this infant research area which utilizes EC methods for the DO of MEMS and points out the challenges that it is facing.**

I. INTRODUCTION

MEMS is currently one of the most promising new areas of engineering. As its name suggests, the MEMS devices integrate both mechanical and electronic components. These components are fabricated on a common silicon substrate by micromachining techniques adopted from integrated circuits (ICs), so they have very small scale which can usually be measured in micrometers. Although it is still a novel research field, more and more commercial applications including accelerometers, gyroscopes, pressure and chemical sensors, microfluidic systems and optical switch turn up in recent years. As the complexity of these devices grows, developing efficient computer-aided design (CAD) tools for MEMS DO becomes an urgent requirement.

This paper focuses on one aspect of the research on MEMS, the emerging evolutionary approaches applied in the DO of MEMS, which highlights the work made by researchers on various issues during the MEMS synthesis process after specifying the limitations of traditional design optimization techniques.

II. LIMITATIONS OF CONVENTIONAL DESIGN OPTIMIZATION OF MEMS

Researchers and engineers have encountered some unique challenges in MEMS DO. One of these challenges lies in analyzing the many interdependent physical phenomena to which MEMS devices are sensitive and working with small-scale geometry. MEMS is a interdisciplinary field which combines studies in mechanical engineering, electrical engineering, electronics, fluid mechanics, optics, chemistry and chemical engineering with a vast spectrum of application areas. Because MEMS is still in its early stage and it involves a large number of disciplines, there is not yet a developed science of design for MEMS. For example, some physical phenomena in the involved disciplines may be still unknown or well understood. Thus, traditional methods like ODE for system level modeling may be hard to be applied.

Another major challenge comes from the expansion of the design search space, when MEMS devices become increasingly more complex and their performance is increasingly more nonlinear. But traditional optimization methods normally work within a local view of optimization in the search space, as it essentially depends on the start points and search direction. With this problem, these traditional deterministic means given the same starting point within the search space will always lead to the same final solution and probably result in sticking at a local optimal point rather than achieving the global optima.

More detailed information on traditional MEMS DO approaches is given in [26].

III. EVOLUTIONARY SYNTHESIS OF MEMS

Synthesis is the reverse of analysis process and it try to find a design meeting the desired functions or behaviors [29]. As optimization is a process searching for best solutions for performance objectives, the synthesis process becomes an optimization problem.

As it becomes difficult for designers and traditional algorithms to search for solutions in the complex design space of MEMS design, the avenue of stochastic methods of DO looks to be a promising approach, especially in the field of Evolutionary Computation (EC). There are numerous successful applications of EC in other engineering disciplines. The ability to handle complex multimodal search landscapes and non-continuous design variables could provide the breakthrough needed to allow reasonably fast design optimization and the design of novel devices beyond a designer's capability in automated design of MEMS.

Because the application of evolutionary techniques to MEMS DO is still in its infancy, there are only a few groups and institutions that are involved into this field. Among them are the University of California at Berkeley, California Institute of Technology, NASA, Michigan State University, Technical University of Denmark, and Cambridge University. Several important conferences publishing papers in this field include Genetic and Evolutionary Computation Conference (GECCO),

978-1-4244-5697-0/10/$25.00 ©2010 IEEE

International Society for Optical Engineering (SPIE) conferences and the American Society of Mechanical Engineers (ASME) conferences.

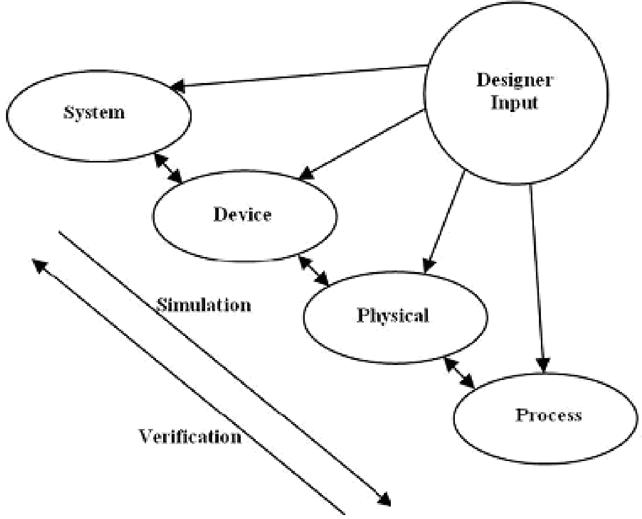

Fig. 1. Modeling subdivision proposed by Senturia [2]

Since H. Li and E.K. Antonsson [6] made the pioneer work that uses genetic algorithm (GA) for the mask layout synthesis, lots of evolutionary techniques have been developed to handle design difficulties or to improve the design efficiency at different levels. Several representative works that EC approaches have been applied for MEMS design automation are given in the following sections.

A. Hierarchical Evolutionary Synthesis of MEMS

Fan et al. [1] implemented an approach combining Genetic Programming (GP) and Bond Graph (BG) for the system level modeling. According to the modeling subdivision (see Figure 1) proposed by Senturia [2], the interactions of the MEMS component with its environment and electronics can be modeled and simulated at the system level. BG [3] is a modeling tool that provides a unified approach to the modeling and analysis of dynamic systems, especially hybrid multi-domain systems. GP [4] is an EC method which involves a graph-type representation, typically the tree structure. In their work, functions will be added as nodes of the tree. Experimental results demonstrate that GP can evolve both the topologies and parameters of corresponding RF MEM devices, namely band pass filters to meet predefined design specifications after a Realizable Function Set was defined. The approach is used as the first step of an automated MEMS synthesis process.

A further research that involves both system level and second level physical layout synthesis is also shown by Fan et al.[5] The second level known as device level in [2] optimizes geometric sizing parameters for basic components, which in most cases are chosen from micromechanical devices with fixed topologies, according to engineering design objectives. The authors approach is to model the design problem as a formal constrained optimization problem, and then solve it with GA. This process is illustrated on the same band pass filter design.

B. Mask Layout Synthesis of MEMS

The second level is 2-D layout of basic structures like beams to form the elementary planar devices. In some cases, if the MEMS is basically a result of a surface micro-machining process and no significant 3-D features are present, design of this level will end one cycle of design. More generally, modeling and analysis of a 3-D solid model for MEMS is necessary. However, even if we have obtained an optimized 3-D device shape, it is still very difficult to produce a proper mask layout and correct fabrication procedures. Automated mask layout and process synthesis tools would be very helpful to relieve designers from considering the fabrication details and focus on the functional design of the device and system. [18]

Evolutionary approach is applied in mask-layout and process synthesis by Li and Antonsson [6]. In their research, GA is applied to a population of geometrically valid mask-layouts to iteratively search for a global optimum individual. The fabrication of each layout is simulated using a 3-D etching simulator called Segs. The iteration of GA continues until the mask-layout with sufficiently close fabricated 3-D shape to a desired 3-D shape specified by users is turned up. The research is refined with object-oriented architecture, enabling the use of any forward process simulator for evaluation [7]. Due to the focus on mask layout and fabrication, their work proposes an automatic synthesis method at the process level.

C. Multi-objective optimization methods

According to the complex nature of MEMS design, in many cases, more than one objective needs to be taken into account. The DO of MEMS can be recognized as a multi-objective optimization process. For example, in designing a meandering resonator, the objectives should match a specified resonant frequency and stiffness of its legs in each direction, while minimizing surface area [16].

The Multi-Objective Genetic Algorithm (MOGA) [8] approached was first adopted by Zhou et al. [9][16][17] to automatically synthesize MEMS designs, specifically meandering resonators . In their experiments, both the topology and size of the devices are generated by MOGA and the geometric validity and performance of each design is evaluated by SUGAR [10][27], a MEMS simulation package. In the MOGA, Pareto optimality (see Figure 2) is used to make it possible to find multiple optimal non-dominated solutions and fitness sharing is applied to maintain its diversity. Based on Zhou's work, Kamalian analyzed the influence of geometric constraints in the resonator case study [28] and extended to the design of more advanced MEMS devices, including accelerometer and gyroscope [12]. Zhang [11] continues Zhou and Kamalian's research with a hierarchical MEMS synthesis and optimization architecture, in which an object-oriented data structure is applied to represent the information of geometrical parameters, connectivity, operation instructions and restrictions within each MEMS design component. This data structure allows flexible and meaningful operations during the iterative process, and also makes the MEMS synthesis framework easily extendable to different designs and topologies. Compare with Fan's work, their study mainly focuses on a lower level, namely physical level, according to Senturia's four levels of MEMS modeling.

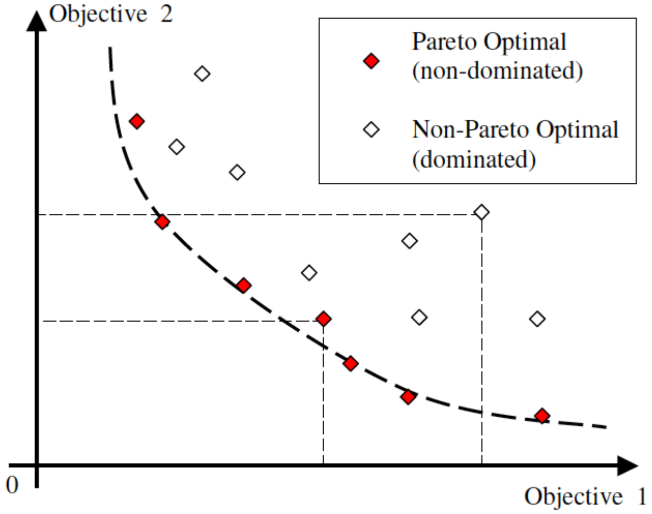

Fig. 2. Pareto optimality in a two-objective minimization problem [12]

The comparison between the performance of MOGA and other methods including Simulated Annealing (SA) [13] and Single-Objective Genetic Algorithm (SOGA) in the DO of MEMS has been made by Kamalian et al. [14] to validate the feasibility of MOGA. The results of evolving a meandering resonator using the methods mentioned above show that the best ranked design in SOGA converges to the objective faster than that in MOGA, but it is stuck at a local optimum. SA can synthesize valid designs faster than genetic algorithms in some cases, but its dependence on a single objective function and the difficulty in finding the global optimum indicate that it is a less robust method for many MEMS synthesis problems.

The similar experiment was conducted by Lohn et al. [15] with a concise and extendable genetic programming language. A novel evolutionary computation encoding scheme that makes all of the phenotypes generated geometrically viable designs is developed to minimize computational cost. As a result, they are able to evolve designs that had similar or better performance to the design presented by Zhou et al. in [16][17] using, on average, less than a third to one half of the number of evaluations. Furthermore, the genetic programming representation supports more complicated structures such as loops, branches and even serpentine springs that hard to evolve in their early research.

D. *Attempts for Robust Design*

As fabrication process variation in MEMS is inevitable in current micromachining techniques, designing MEMS that is insensitive to fabrication process variation becomes an important issue. The notion of robust design is introduced to improve the quality of products with significant variations in their manufacturing process. Several attempts for robust design in MEMS DO have been made.

A robust design scheme called Genetic Algorithms with Robust Solution Searching Scheme is introduced by Ma et al. [19] in the mask-layout and process synthesis problem. In their approach, noise factors are integrated into the design process using a GA to design a solution. More specifically, a random noise with appropriate tested distribution is added into the parameter phenotype. In the case study, this method shows its capability for addressing mask misalignment.

Hornby et al. [20] presents two modifications for evaluating candidate designs in their EA loops to achieve better robustness. One is to add location noise, which intends to determine the differences between the actual dimensions of the design and the design blueprint in multiple evaluations. The other is to apply pre-stress to the design, which incorporates the effects of warping during the extreme heat of fabrication. Their further study is to test whether these robust designs will work correctly in reality.

Fan et al. [21] formulate the robust design problem as a multi-objective constrained optimization problem with two design objectives to be minimized in the layout synthesis of MEMS, the squared error to the nominal design and sensitivity. Then an efficient algorithm NSGA-II [22] is used to find trade-off solutions. In this approach, only slight modification in the objective function can achieve robustness without any change in the algorithm process. An Improved DE Algorithm based on Stochastic Ranking (IDE-SR) which outperforms the previous study on NSGA-II for robust design of MEMS is also developed by Fan et al. [23].

E. *Efficiency Improvement*

Due to the expensive computational costs during simulation for large populations in each generation, the evolutionary DO of MEMS is a complex and time-consuming process. Therefore, improving the design efficiency to find a global optimal design in a practical time period becomes a very significant issue.

One challenge comes from the popular Finite Element Analysis (FEA) for the numerical modeling of MEMS, which may take hours per evaluation for large population and hampers the iterative design process. The development of some reduced-order modeling tools, like SUGAR based on Modified Nodal Analysis, is an attempt to break the limitation of the simulation speed.

Zhang [11] proposes a hybrid evolutionary computation method with two levels of optimization techniques: global stochastic search and gradient-based local optimization. This research extends Zhou's work [17] by integrating a gradient-based local optimization technique at the end of global search by MOGA to further optimize and fine-tune promising designs with fixed design geometries in a computational effective manner.

Because certain qualitative aspects of many design candidates can be easily evaluated by a human designer while extremely difficult or computationally costly to be mathematically modeled and simulated, the Interactive Evolutionary Computation (IEC) method is introduced to embed the human designer's visual inspection and domain knowledge into the computer-aided MEMS design process. A work in this line was carried out by Kamalian et al. [24]. The IEC algorithms are based on the non-interactive EC algorithms to achieve local optimization. A case study on a meandering resonator design is presented to indicate the effectiveness of the IEC approach. The non-interactive phase produces the initial population for the IEC to search. The results show that the non-interactive only approach produces less satisfactory results compared to results achieved by using the IEC-enhanced approach.

To overcome the human fatigue in IEC and compensate for the lack of good-pattern recognition capabilities in hybrid GAs, Interactive Hybrid Computation (IHC) algorithm is developed by Zhang [11]. To reduce human fatigue, user evaluation is only applied at certain predefined generations and qualified designs will be subject to local optimization during the MEMS synthesis process. Meanwhile, IHC uses the results of the local optimization to refine fitness values of preferred designs, reducing the influence of subjectivity and non-consistency of the human evaluation.

Because the initial population of designs to start the MOGA process derives from either user supply or random generation, a Case-Based Reasoning (CBR) approach developed by Cobb et al. [25] can be incorporated in the MEMS design process to accelerate the synthesis process. Maintaining previously successful MEMS designs and sub-assemblies as building blocks stored in an indexed case library, the CBR serves as a knowledge base to provide designs close to current objectives and store the current best solutions for future use. The results of their experiment demonstrate that combination of CBR and MOGA synthesis tools can help increase the number of optimized design concepts.

IV. CONCLUSION

This paper summarizes the current research in the evolutionary approaches applied for optimizing MEMS design. These approaches lies in different aspects of a design process, from a system level synthesis down to a lower level mask layout synthesis for the fabrication process, from design efficiency improvement by reducing the total number of evaluations to robust design for counteract fabrication uncertainty. Compared with the traditional optimization method for automated design of MEMS, these evolutionary approaches is more capable for multi-objective DO and maintain better performance for searching global optimum solution. Furthermore, multi-objective optimization problem for MEMS design can be better solved by effective MOEAs such as MOGA and NSGA-II.

Although with great potential, this field is still in an initial stage and needs to address a lot of challenges in its future development. For example, while many approaches in device level synthesis have been proposed, we are still lack of a synthesis tool that can integrate DO for all levels of design. The connection between different levels is only detailed or defined in a few cases. Besides, we have robust techniques in device level and process level designs, but we still lack these criteria in system level design.

REFERENCES

[1] Z. Fan, E.D. Goodman, J. Hu, R.C. Rosenberg, and K. Seo, “System-Level Synthesis of MEMS via Genetic Programming and Bond Graphs,” *Proceedings of the 2003 Genetic and Evolutionary Computation Conference*, pp. 2058-2071, 2003.

[2] S.D. Senturia, *Microsystem Design,* Kluwer Academic Publishers, 2001.

[3] R.C. Rosenberg, “Reflections on Engineering Systems and Bond Graphs,” *Trans. ASME J. Dynamic Systems, Measurements and Control,* 115, pp. 242-251, 1993.

[4] J.R. Koza, *Genetic Programming: On the Programming of Computers by Means of Natural Selection*, MIT Press, 1992..

[5] Z. Fan, E.D. Goodman, J. Wang, R.C. Rosenberg, K. Seo, and J. Hu, “Hierarchical Evolutionary Synthesis of MEMS,” *Proceedings of the Congress on Evolutionary Computation,* vol. 2, pp. 2320-2327, 2004.

[6] H. Li, and E.K. Antonsson, “Evolutionary Techniques in MEMS Synthesis,” *Proceedings. DETC'98, 1998 ASME Design Engineering Technical Conferences, Atlanta, GA*, 1998.

[7] H. Li, and E.K. Antonsson, “Mask-Layout Synthesis through Evolutionary Algorithm,” *MSM’99, Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators, San Juan, Puerto Rico*, April 1999.

[8] D.E. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison-Wesley Publishing Company, Reading, Massachusetts, 1989.

[9] N. Zhou, B. Zhu, A.M. Agogino, and K.S.J. Pister, “Evolutionary Synthesis of MEMS MicroElectronicMechanical Systems Design,” *Proceedings of the Artificial Neural Networks in Engineering (ANNIE2001),* 11, ASME Press, pp.197-202, 2001.

[10] SUGAR, Simulation Research for MEMS, http://wwwbsac.eecs.berkeley.edu/cadtools/sugar/sugar/

[11] Y. Zhang, “MEMS Design Synthesis Based on Hybrid Evolutionary Computation,” *PhD Thesis*, Department of Civil and Environmental Engineering, University of California at Berkeley, 2006.

[12] R. Kamalian, “Evolutionary Synthesis of MEMS Devices,” *PhD Thesis*, Department of Mechanical Engineering, University of California at Berkeley, 2004.

[13] S. Kirkpatrick, C.D. Gelatt, and M.P. Vecchi, “Optimization by simulated annealing,” *Science*, vol. 220, pp. 671–680, 1983.

[14] R. Kamalian, N. Zhou, and A.M. Agogino, “A Comparison of MEMS Synthesis Techniques,” *Proceedings of the 1st Pacific Rim Workshop on Transducers and Micro/Nano Technologies*, Xiamen, China, pp. 239-242, July 22-24, 2002.

[15] J.D. Lohn, W.F. Kraus, and G.S. Hornby, “Automated Design of a MEMS Resonator,” *Proceedings of the Congress on Evolutionary Computation,* pp. 3486-3491, 2007.

[16] N. Zhou, A.M. Agogino, and K.S.J. Pister, “Automated Design Synthesis for Micro-Electro-Mechanical Systems (MEMS),” *Proceedings of the ASME Design Engineering Technical Conference,* pp.68-73, 2002.

[17] N. Zhou, “Simulation and Synthesis of MicroElectroMechanical Systems,” *PhD Thesis*, Department of Mechanical Engineering, University of California at Berkeley, 2002.

[18] L. Ma, and E.K. Antonsson, “Automated mask-layout and process synthesis for MEMS,” *Technical Proceedings of the International Conference on Modeling and Simulation of Microsystems*, pp. 20-23, 2000.

[19] L. Ma, and E.K. Antonsson, “Robust Mask-Layout Synthesis for MEMS,” *Technical Proceedings of the 2001 International Conference on Modeling and Simulation of Microsystems*, pp. 128-131, 2001.

[20] G.S. Hornby, W.F. Kraus, and J.D. Lohn, “Evolving MEMS Resonator Designs for Fabrication,” *Proceedings of the 8th international conference on Evolvable Systems: From Biology to Hardware*, pp. 213-224, 2008.

[21] Z. Fan, J. Wang and E.D. Goodman, “An Evolutionary Approach For Robust Layout Synthesis of MEMS,” *Proceedings of 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp. 1186-1191, 2005.

[22] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, “A fast and elitist multiobjective genetic algorithm: NSGA-II,” *IEEE Transactions on Evolutionary Computation,* vol. 6, no. 2, pp. 182–197, April 2002.

[23] Z. Fan, J. Liu, T. Sørensen, and P. Wang, “Robust Layout Synthesis of MEMS Components Using Improved Differential Evolution,” *IEEE Transactions on Industrial Electronics* , vol. 56, issue 4, pp. 937-948, 2009.

[24] R. Kamalian, H. Takagi and A.M. Agogino, “Optimized Design of MEMS by Evolutionary Multi-objective Optimization with Interactive Evolutionary Computation,” *Proceedings of GECCO 2004 Genetic and Evolutionary Computation Conference,* Seattle, Washington, pp. 1030-1041, June 26-30, 2004.

[25] C. Cobb, Y. Zhang, and A.M. Agogino, “An Integrated MEMS Design Synthesis Architecture Using Case-Based Reasoning and Multi-Objective Genetic Algorithms,” *Proceedings of 2006 SPIE Smart Materials, Nano- and Micro-Smart Systems*, 2006.

[26] S. Achiche, Z. Fan and and F. Bolognini, “Review of Automated Design and optimization of MEMS,” *IEEE International Symposium on Industrial Electronics,* pp. 2150-2155, June 2007.

[27] D. Bindel, J.V. Clark , N. Zhou, S. Bhave, Z. Bai, J. Demmel, K.S.J. Pister, “Sugar: Advancements in a 3D Multi-Domain Simulation Package for MEMS.” Proceedings of the Microscale Systems: Mechanics and Measurements Symposium, Portland, OR, June 4, 2001.

[28] Kamalian, R., Agogino, A.M., and Takagi, H., “The Role of Constraints and Human Interaction in Evolving MEMS Designs: Microresonator Case Study,” Proceedings of DETC/DAC, 2004 Design Engineering Technical Conference, Design Automation Track, Paper # DETC2004-57462, CD ROM, ISBN # I710CD, 2004.

[29] E.K. Antonsson, and J. Cagan, *Formal Engineering Design Synthesis*, Cambridge University Press, Cambridge, 2001.