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Duke University

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13. ABSTRACT (Maximum 200 Words) Duke University in partnership with Carnegie Mellon University and the MCNC MEMS Technology Applications Center has performed a research effort to develop new technologies in the area of integrated microelectromechanical systems (MEMS). The research in Integrated Microelectromechanical Process and Circuit Technology (IMPACT) was organized and structured to promote key advancements in MEMS that leveraged state-of-the-art technologies. The goals of the program were based on the need to decouple circuit and process design activities, and thereby promote a common "front-end" to MEMS design tools, as has been done in the integrated circuit arena. Specifically, the goal of IMPACT was to develop a circuit-level design capture and optimization tool set for MEMS technology having a beneficial impact comparable to that of physical-level schematic capture and layout tools developed for IC technology.				
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1 Program Goals

Duke University in partnership with Carnegie Mellon University and the MCNC MEMS Technology Applications Center has performed a research effort to develop new technologies in the area of integrated microelectromechanical systems (MEMS). The research in Integrated Microelectromechanical Process and Circuit Technology (IMPACT) was organized and structured to promote key advancements in MEMS that leveraged state-of-the-art technologies. The goals of the program were based on the need to decouple circuit and process design activities, and thereby promote a common “front-end” to MEMS design tools, as has been done in the integrated circuit arena. Specifically, the goal of IMPACT was to develop a circuit-level design capture and optimization tool set for MEMS technology having a beneficial impact comparable to that of physical-level schematic capture and layout tools developed for IC technology. To accomplish this goal, IMPACT pursued the following tasks:

- generate reusable MEMS component models via visual modeling
- obtain efficient early estimates of performance via static design analysis
- control manufacturing sensitivities via design centering

The IMPACT Project emphasized a multidisciplinary collaboration of engineers and scientists engaged in computer language, numerical analysis, design optimization, synthesis, and integrated microdevice fabrication research. Specifically, the IMPACT Project made the following unique and innovative contributions:

- MEMS visual specification design capture that employs graphical rendering techniques to enable direct manipulation of desired MEMS function and composition and efficient compilation of VHDL-AMS reusable component models.
- MEMS VHDL-AMS modeling practices and models that promote establishing foundry interfaces via component design reuse and parameterized back-annotation to physical shape. Unified, hierarchical abstractions of MEMS characterized by integro-differential equations are supported that can accurately represent theoretical design concepts and can then be decomposed into physical abstractions.
- MEMS static design analysis that establishes early estimates of performance without incurring the overhead of complex device mesh and circuit nodal simulation
- MEMS design centering techniques that leverage the current work in numerical solution engines for MEMS models that address the influence of first-order sensitivity gradients of physical and process parameters on circuit function.

2 TASK 1.0: IMPACT MEMS Tool Technology Development

Task 1.1: MEMS Visual Design Capture

The goal of this task was to develop graphical renderings for defining MEMS system specifications by building a new design capture capability on top of textual hardware description languages. This allows for direct behavioral manipulation and construction. The developed design capture

capability reduced textual programming by supporting the compilation of MEMS specifications into reusable components described in VHDL-AMS. The work was divided into three tasks:

- 1) Visual specification and design capture
- 2) Reusable component modeling
- 3) Model and schematic characterization

Results

This work has resulted in the achievement of three milestones in the area of structured topological design (VIVID tool), a visual programming language, and the use of signal flow graphs for MEMS models. These three milestones are illustrated below in Fig. 1.

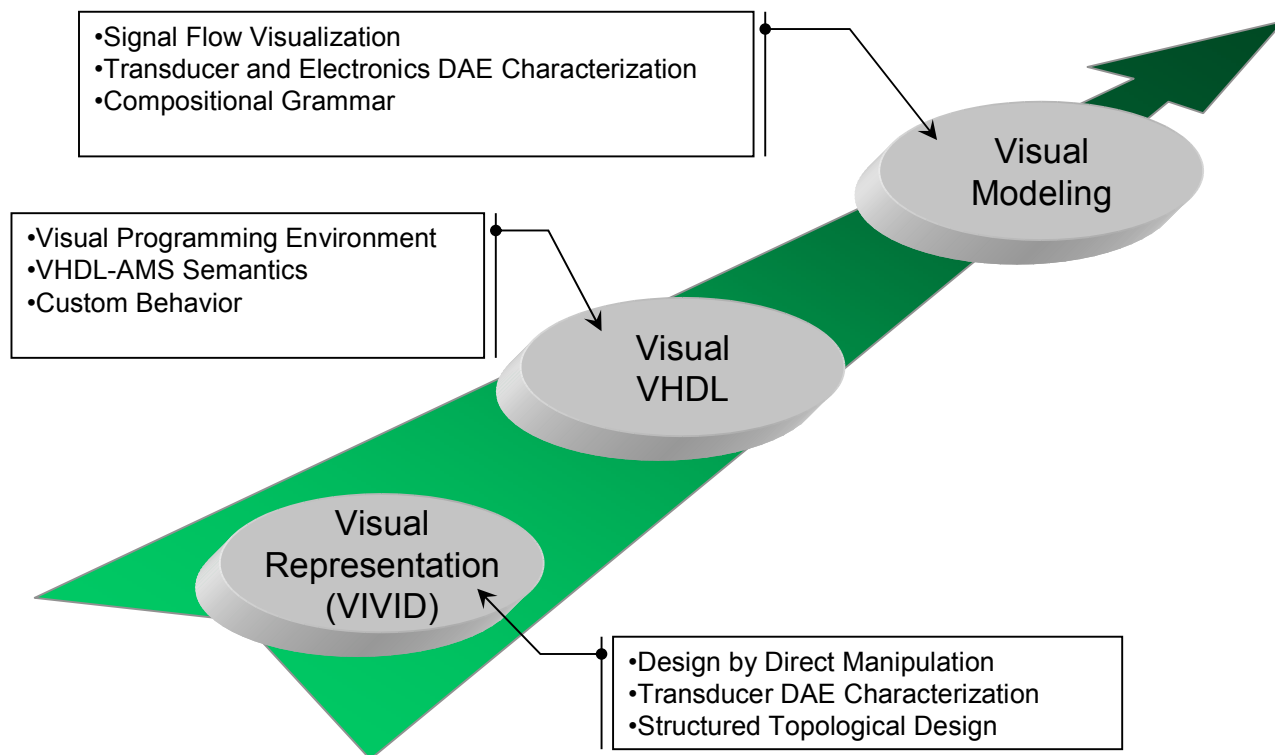


Fig. 1. Design capture milestones in IMPACT

The motivation for visual modeling was threefold: 1) reduce the programming burden in MEMS modeling with a visual language; 2) simplify the modeling process by providing higher level constructs; 3) gain insight into model dynamics through visualization. To support the visual language, a data model was implemented which enforces the syntax and structure of VHDL-AMS. It covers the continuous time subset of the VHDL-AMS grammar. The data model encodes the constructs of the language such as types, natures, constants, terminals, quantities, packages, entities, architectures and libraries.

A Visual Modeling of Electromechanical Systems (VMEMS) tool was developed. The intent of VMEMS is to make high-level abstract operations available to the model designer in a signal flow

environment. This allows the designer to deal with complex operations such as spatial discretization and spatial differentiation. The result is a familiar environment that makes it easy to describe the behavior of an electromechanical system and reduces the programming burden for the model designer using VHDL-AMS. To make the VMEMS tool useful, the user must have quick access to all the available objects of the language. Therefore, a tree view for VHDL-AMS libraries has been implemented that allows the user to quickly view and edit any VHDL-AMS object constructed. The tree view and signal flow graph editor work together to define the equations which define the behavior of any architecture. Work was then completed on a prototype of the VMEMS tool and documentation.

Following the formal methodology proposed at UT Austin, a graph-based visual language was specified and was implemented. The type composition, query language, action language and graphical attributes were defined. They encompass the basic constructs of signal flow graphs which include constants, variables, operators and signals. An initial algorithm for producing the system of equations from the graph has been implemented. This work resulted in a MS thesis.

Task 1.2: MEMS Static Design

This work addressed the need to obtain efficiently early performance estimates of key electrical and mechanical metrics by static model profiling instead of dynamic model simulation. Element couplings are discerned and verified, and aggregate system timing, frequency response, energy consumption, and operating range are estimated.

The general goal of this work was to develop a new analysis capability for MEMS that was faster than a full analog solver (like SPICE) and more flexible. The work necessarily focused on two critical issues of static analysis: 1) component model complexity, and 2) compilation techniques. The introduction of arbitrarily complex device models had the potential to seriously impact circuit simulation issues. Thus, the work looked at simulatability issues in behavioral component modeling of MEMS and optimized modeling methodologies and compilation techniques.

Results

This work addressed important issues of the implications of how differential and algebraic equations are written, not from the perspective of modeling physical behavior but rather from the perspective of simulatability. Altering the form of the differential and algebraic equations offered an interesting way of influencing the formulation of the Jacobian matrix and the resulting structure/sparseness. This aspect influences simulatability. This work resulted in an MS thesis.

Task 1.3: MEMS Design Optimization

The goal of this work was to leverage the basic evaluative capabilities of integro-differential equation solution engines and characterizations of tribological phenomena to pursue circuit optimization via design centering. Nominal values of circuit parameters are determined to “center” the circuit in its performance space to minimize potential drifts caused by variances in physical implementation and fabrication processes. Thus, this work was motivated by two things: 1) reduce

the effect of device parameter variations on MEMS yield and performance; and 2) leverage microelectronics design centering expertise in MEMS yield management. The work was divided into three tasks: 1) investigate commonly used yield optimization methods in IC design; 2) identify and test promising yield optimization techniques; and 3) study MEMS specific performance characteristics of chosen optimization techniques.

Optimization was applied to the device level, the model level and the system level, as shown below in Fig. 2. A two-step process aimed at quality optimization of MEMS was demonstrated. The first step uses the Worst-Case-Distance-Driven (WCD) Approach introduced in our earlier work to obtain a first-step design solution. Due to its robust nature the WCD yields a feasible solution even though the starting point may lie outside the region of feasibility. The second step uses the aforementioned design point as an initial feasible solution and implements a desirability-function-based method for reducing statistical performance variability. Search algorithms for both design steps incorporate nonlinear programming principles.

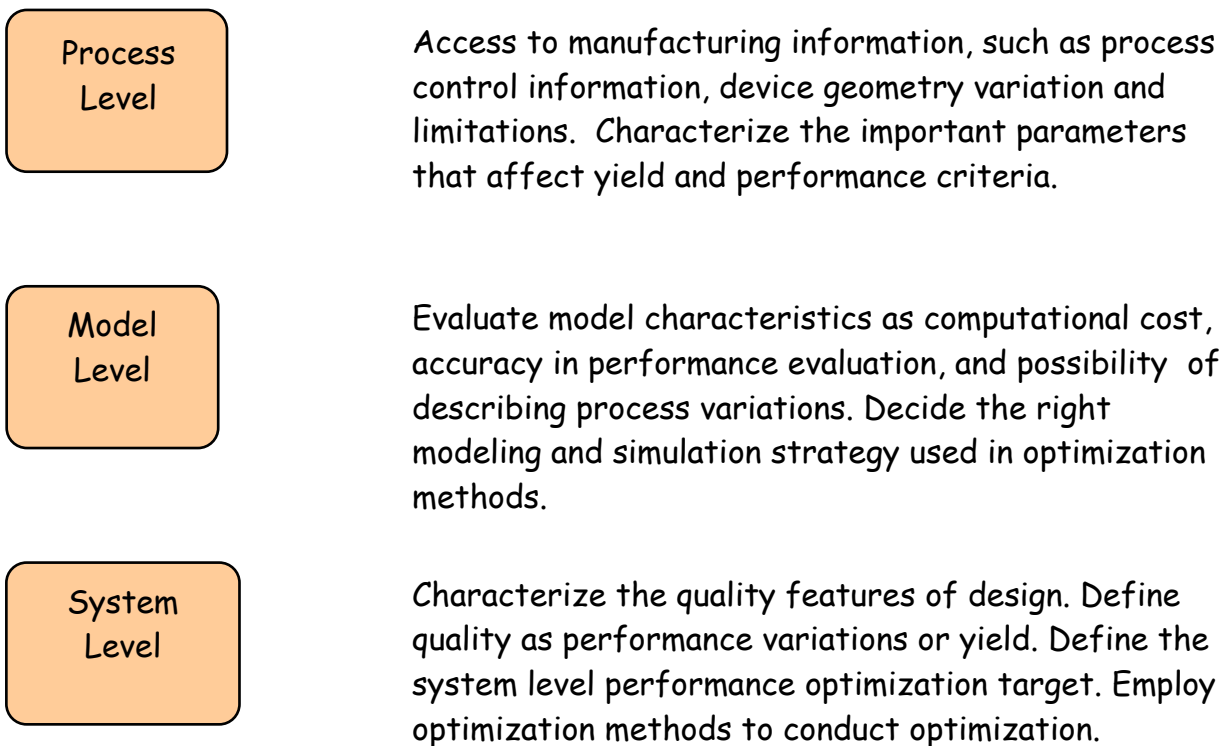


Fig. 2. Optimization levels identified in IMPACT.

A three-step method was also demonstrated, where the step involves application of the Taguchi method using a factor level analysis. This method is illustrated in Fig. 3. Results in applying this method to a commercial accelerator are shown in Table 1. Yield shows continued improvement at each sequential step.

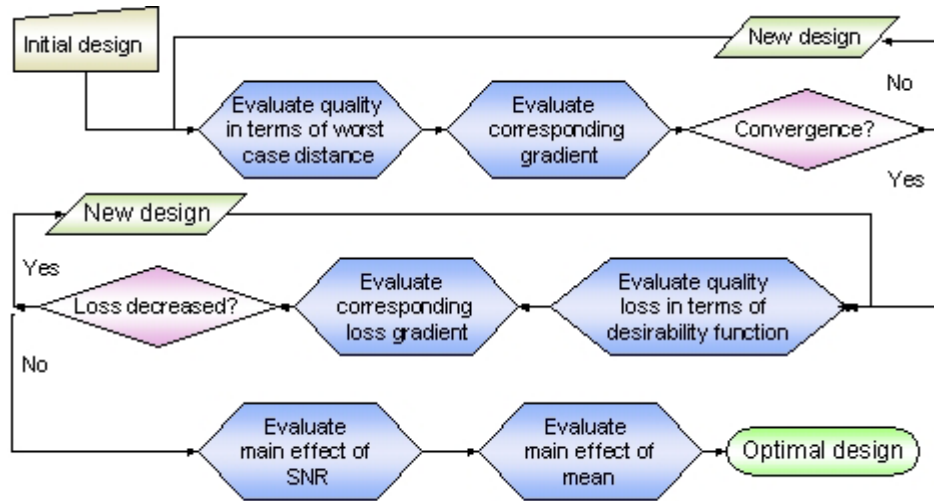


Fig. 3. Three step quality management

Table 1 : Design and design evaluation before and after each step of quality optimization (sensitivity target = 5mv/g)

Design Evaluation	Initial	WCD	SPVR	Taguchi
Poly Thickness	2	2.5	2.5	2.5
Beam Width	2	2	2.3	2.5
Beam Length	268	306.7	303.5	261
Overlap Length	110	140.3	206.9	227
Electrode Length	120	142.3	208.9	230
Electrode Width	3	3.7	5.7	3
Air Gap	1.3	2	2.1	2
Mass Length	400	416.3	554.2	692
Mass Width	50	82.6	88.4	142
Finger Number	46	46	46	88
Nominal Sensitivity	3.6mv/g	4.4mv/g	3.8mv/g	4.2mv/g
Sensitivity Mean	4.5mv/g	6.5mv/g	4.9mv/g	5.2mv/g
Sensitivity Deviation	1.3mv/g	2.6mv/g	1.3mv/g	1.1mv/g
Trimming Yield	42.76%	50.48%	63.92%	79.34%

Task 1.4: VHDL-AMS MEMS Component Modeling

The goal of this work was to represent function specifications of complex integrated electrical and mechanical systems in a core set of extensible representations and constructs. To carry out this effort, the following tasks were performed: 1) development of a system-level modeling methodology for MEMS; 2) development of parameterizable (scalable) macromodels for MEMS

devices with emphasis on reusability, readability and interoperability; 3) demonstration of the methodology using representative examples: cantilever, accelerometer, and pressure sensor.

Results

A formal methodology for behavioral macro-modeling of MEMS was developed and demonstrated. The methodology involves the following steps

1. **Symbolic Finite Element Modeling** - MATLAB's symbolic toolbox was used to develop the finite element modeling routine. The routine generates symbolic mass and stiffness matrices for the microstructure under consideration, which are inputs to the model-order reduction algorithm. Structures with only beam elements, like cantilevers, accelerometers and resonators, are currently supported.
2. **Model-order reduction** - Krylov subspace methods are used to reduce the order of the finite element model. A symbolic version of the Lanczos algorithm is used to generate the Krylov subspace. The Lanczos algorithm has been extended for direct application on the mass and stiffness matrices, so that symmetry and physical meaning is not lost while reducing.
3. **Modeling and simulation** - Initial simulations were performed using MATLAB and verified with data from literature. Models for cantilever beams, fixed-fixed beams and fixed-guided beams have been developed and verified. VHDL-AMS models for circuits commonly used in MEMS devices have also been developed and simulated using AdvanceMS from Mentor Graphics.

The above methodology has resulted in novel automatic macromodeling methodology to generate *small* and *scalable* macromodels for microstructures. Higher order finite element (FE) models, which capture the dynamic behavior of the microstructure, are projected onto a Krylov subspace of smaller dimension to obtain a reduced-order model. The Lanczos algorithm is used to generate the Krylov subspace in a fixed number of computational steps, predetermined by the size of the reduced-order model. The size of the reduced-order model is chosen depending on the range of frequencies where matching with the original model is desired. The Krylov subspace method is deterministic in the sense that it does not involve an iterative simulation-verification procedure to obtain the reduced-order model. The FEM routine and the Lanczos algorithm were implemented using MATLAB's Symbolic Toolbox to ensure scalability. A macromodel of the folded-flexure microresonator is shown here to demonstrate the modeling methodology. Expressions for the effective mass and spring-constant of the folded-flexure were obtained and compared with results obtained from FEM, analytical solution and NODAS. The design specifications of the resonator and the simulation results for comparison were obtained from CMU's High Q Resonator Canonical Design Problem available at

http://www.ece.cmu.edu/~mems/projects/memsyn/canonical_resonator/index.shtml

The results from the reduced-order model match well with those from FEM, analytical equations and NODAS. Figure 4 depicts the folded flexure structure of the comb drive used in this study.

3 TASK 2.0: IMPACT MEMS Technology Demonstration

The technologies developed under the IMPACT Project have been deployed in technology demonstration projects to maximize potential system design impact, user application benefit, and technology base advancement.

Reusable Component Models

Versions 1.0 and 2.0 of parameterizable VHDL-AMS were published on the IMPACT website.

MEMS Yield Optimization

Our success with the three-step optimization method described above motivated discussions with IntelliSense Corp. regarding the possible technology transition of the technique. The key issues we are working on to explore the usefulness of quality optimization in Intellisuite were:

- how many iterations are required in the optimization process to achieve adequate convergence?
- demonstrate that the optimization methods are efficient, and that they can achieve an optimized design whose dimensions exceed the tolerances of the fabrication process ($\pm 10\%$ dimensional variance).
- can the third step of the optimization method (Taguchi method) be automated?
- apply scalable reduced order models to produce computationally efficient models for use in optimization rather than analytical models.

To facilitate the technology transfer of design optimization, computational cost issues of optimization algorithms have been evaluated. The Worst Case Distance method demonstrates a smaller number of iterations (1-2 iterations) before convergence compared to the Statistical Performance Variability Reduction method that requires 10-20 iterations. Both of these methods need similar numbers of simulation calls. This result was demonstrated at the MSM2001 conference.

The primary challenge we faced in technology transition was developing scalable reduced order models of a particular device that are sufficiently detailed and computationally efficient. Practical MEMS designs are captured in a detailed FEM model. To perform design optimization, it is necessary to extract a reduced order model that carries sufficient detail of the device design to satisfy the designer's needs. This model must then be used in the looping optimization algorithms many times, which builds computational overhead. Ultimately, we must be able to estimate the costs associated with these tradeoffs so that a designer knows the costs and benefits of optimization.

RF MEMS Design

We pursued evaluation of IMPACT technology in collaboration with Microcosm Technologies, the makers of MEMCAD. We developed a design optimization-based method for designing

piezoelectric cantilever switches for RF circuits. The cantilever is a four-layer structure comprising a layer of PZT and a layer of SiN sandwiched between two electrode layers. The upper electrode is made up entirely of gold while the lower electrode is made of polysilicon. The tip has an underlying gold pad for contacting the RF lines. A potential difference is applied between the upper and lower electrodes thereby facilitating the piezoelectric effect. The direction of polling (preferential polarization) is along the z axis in the same direction as the electric field. Due to the piezoelectric effect, the PZT layer extends along the x direction - held to lie along the beam. The PZT layer is in 'no-slip' contact with the underlying SiN. This differential strain condition across the layers results in an axial force plus bending moment situation similar to the one explained by Timoshenko's seminal paper on bimetal thermostats. Bending in turn causes the beam to deflect downward with the gold pad making contact with the RF lines. We investigated the application of design optimization methods to the RF switch design. The design variables included film thickness and beam dimensions. However, none of these variables impact yield optimization, and we discontinued this effort.

Reduced Order Models for Optical BioMEMS

The objective of the effort is to develop reduced models for optical detection processes in bioMEMS sensors for system level simulation. This work was done in collaboration with CMA, Inc. As a representative example, a glucose detection system based on colorimetric detection was chosen. The glucose sensor is a catalytic-affinity based biosensor.

The glucose detection takes place in two steps

i. D-Glucose + Oxygen -----> Gluconic Acid + Hydrogen Peroxide

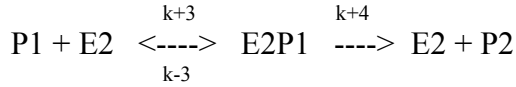
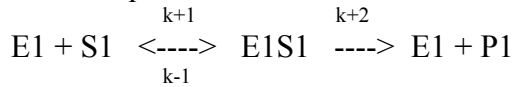
ii. 2 Hydrogen Peroxide + Phenol + 4-Aminoantipyrene -----> Quinoneimine + 4 Water

In the first step D-Glucose is oxidized in the presence of the enzyme Glucose Oxidase (which is highly specific to D-Glucose) to gluconic acid and hydrogen peroxide. The second step is the color reaction where hydrogen peroxide reacts with 4-aminoantipyrene in the presence of the enzyme peroxidase to produce quinoneimine. Quinoneimine is a red-violet compound which absorbs at 546nm. The concentration of quinoneimine is determined by measuring the absorbance of the product at 546nm.

The absorbance is proportional to the concentration of quinoneimine according to the Beer-Lambert's law. The concentration of quinonimine is proportional to the concentration of glucose.

There are two methods by which the concentration can be determined, the end-point method or the kinetic method. In the end-point method the reaction is allowed to proceed to completion and the absorbance which is propotional to the concentration is measured. In the kinetic method the rate of change of absorbance is measured, which is proportional to the rate of the reaction. The rate of the reaction is proportional to the concentration under certain assumptions.

i. **Enzyme reaction kinetics** - The enzymatic reactions are modeled by using Michealis-Menten kinetic equations.



After writing the rate equations using Michealis-Menten hypothesis that concentration of enzyme-substrate complex is constant we get the following differential equations.

$$\frac{d}{dt}[S1] = -k_{+2} \frac{[E1t][S1]}{[S1] + Km1}$$

$$\frac{d}{dt}[P1] = k_{+2} \frac{[E1t][S1]}{[S1] + Km1} - k_{+4} \frac{[E2t][P1]}{[P1] + Km2}$$

$$[P2] = [S1](t=0) - [S1] - [P1]$$

[E1t] = total concentration of glucose oxidase

[S1] = concentration of glucose in the mixture = [Glucose in Sample] x Dilution Factor

Km1 = Michaelis-Menten constant for 1st reaction

[E2t] = total concentration of peroxidase

[P1] = concentration of hydrogenperoxide

Km2 = Michaelis-Menten constant for 2nd reaction

[P2] = concentration of quinoneimine

ii. Absorption spectroscopy modeling

Absorption is modeled using the Beer-Lambert's law, which states that

$$A = \log(I_0/I) = \epsilon l C \quad \text{where}$$

A = absorbance,

I₀ = incident intensity,

I = measured intensity

ε = extinction coefficient of absorbing substance (quinoneimine) at the particular wavelength

l = optical path length

C = [P2] = concentration of absorbing substance

$$A = \epsilon l [P2]$$

$$dA/dt = \epsilon l d[P2]/dt$$

[P2] is obtained by solving the rate equations. The results from simulating the rate equations in MATLAB are shown above. We have applied these reduced order models and have made experimental measurements to verify rate constants. Based upon these results we have been able to

modify the concentrations of reagents in order to accelerate the production of quinoneimine, so that optical detection of this color product can be performed in less than 60 sec rather than thousands of seconds. This result will have an important impact on point-of-use microdialysis that allows real time monitoring of a patient's glucose, lactate, urea, etc. levels.

4 Publications

Publications from the IMPACT group over the last two years are summarized as follows:

Journals

- A. Dewey, V. Srinivasan, and E. Icoz, "Towards a Visual Modeling Approach to Designing Microelectromechanical System (MEMS) Transducers," *Journal of Micromechanics and Microengineering*, vol.9, no. 4, pp. 332-340, December 2000.
- A. Dewey, H. Ren, and T. Zhang, "Behavioral Modeling of Microelectromechanical Systems (MEMS) with Statistical Performance-Variability Reduction and Sensitivity Analysis," *IEEE Transactions on Circuits and Systems - II*, vol. 47, pp. 108-113, February 2000.

Conferences

- A. Dewey, H. Dussault, J. Hanna, E. Christen, G. Fedder, and M. Maher, "Energy-Based Characterization of Microelectromechanical Systems (MEMS) and Component Modeling Using VHDL-AMS," *Proc. Modeling and Simulation of Microsystems, Semiconductors, Sensors, and Actuators (MSM 99)*, San Juan, Puerto Rico, 19-21 April 1999.
- A. Dewey, and E. Icoz, "Visual Modeling and Design of Microelectromechanical Systems (MEMS) Transducers," *Proc. Modeling and Simulation of Microsystems, Semiconductors, Sensors, and Actuators (MSM 99)*, San Juan, Puerto Rico, 19-21 April 1999.
- A. Dewey, T. Zhang, H. Ren, and J. Wu, "Parametric Regression Analysis of Microelectromechanical Resonators," *Proceedings IEEE/VIUF International Workshop on Behavioral Modeling and Simulation (BMAS '98)*, Orlando, FL, October 1998.
- A. Dewey and R. Fair, "Microelectromechanical Systems (MEMS) Design and Design Automation Research at Duke University," *Proc. Modeling and Simulation of Microsystems, Semiconductors, Sensors, and Actuators (MSM 98)*, pp. 174-179, Santa Clara, CA, 6-8 April 1998.
- V. Srinivasan, A. Jog, and R. Fair, "Scaleable Macromodels for Microelectromechanical Systems", *Proceedings of The Modeling and Simulation of Microsystem 2001 Conference*.
- H. Ren, R. Fair, and A. Jog, "MEMS Quality Optimization", *Proceedings of The Modeling and Simulation of Microsystem 2001 Conference*.

5 Personnel Status

A summary of the personnel working on the IMPACT project is given below. Anand Jog completed his work as a post doc in January, 2001.

Mr. Ted Harder
Masters, Electrical and Computer Engineering
Visual Modeling

Mr. Vijay Srinivasan
Masters, Electrical and Computer Engineering
VHDL-AMS MEMS Component Modeling

Ms. Hong Ren
Masters, Electrical and Computer Engineering
Yield Optimization

Mr. Jiuli Lu
Masters, Electrical and Computer Engineering
Static Analysis

Mr. Amrit Vivekanand
Masters, Electrical and Computer Engineering
VHDL-AMS MEMS Component Modeling

6. Total Money Spent

As of 9/02/01, the total amount of money spent on the IMPACT project was \$1,343,519 (preliminary estimate).