

Design of Reconfigurable Composite Microsystems Based on Hardware/Software Co-design Principles¹

Tianhao Zhang, Krishnendu Chakrabarty and Richard B. Fair
Department of Electrical and Computer Engineering
Duke University, Durham, NC 27708-0291, {tzhang, krish, rfair}@ee.duke.edu

ABSTRACT

Custom microsystems are expensive, inflexible, and unsuitable for high-volume production. We address this problem by leveraging hardware/software co-design principles to design reconfigurable composite microsystems. We partition the system design parameters into nonreconfigurable and reconfigurable categories. In this way, the operational flexibility is enhanced and the microsystems are designed for a wider range of application. In addition, the Taguchi robust design and the response surface methodologies are used to make the system robust. A case study is presented for a microvalve, which serves as a representative microelectrofluidic device.

Keywords: Application flexibility, nonreconfigurable and reconfigurable design parameters, response surface, robustness, Taguchi method.

1 Introduction

Composite microsystems that incorporate microelectromechanic and microelectrofluidic devices are emerging as the next generation of system-on-a-chip. A number of design methodologies for microsystems have recently been proposed [1], [2], [3]. These methods lead to robust microsystems that meet performance goals but are relatively insensitive to design parameter variations. However, they are tailored towards “custom microsystems” whose components are designed to operate within a narrow range of their design parameters. This leads to expensive and inflexible systems that are not amenable to large-volume production. This is one of the main obstacles facing composite microsystems development [4].

We propose a reconfigurable composite microsystem design methodology that leverages hardware/software co-design principles to achieve functional unit reusability. It provides design flexibility by allowing software to be compiled efficiently for a modular hardware platform [5]. By focusing on the specific characteristics of composite microsystems, we develop an analogy between microsystem components and the hardware and software components of a microelectronic system. We

show that by partitioning the design parameters of microsystems into two categories—nonreconfigurable and reconfigurable design parameters (referred to as *NRDPs* and *RDPs*, respectively)—we can make the microsystem performance meet the flexibility requirement and be suitable for a wider range of applications. While the values of the *NRDPs* are determined at fabrication time, the values of the *RDPs* are configured (programmed) during operation. This allows the system to conform to a wider range of performance specification. The key challenges here include the following: (i) partition the set of design parameters to *NRDPs* and *RDPs*; (ii) determine the values of the *NRDPs* to make the system performance less sensitive to variation of *NRDPs*; (iii) exploit the synergy between *NRDPs* and *RDPs* to increase performance flexibility. Thus, given a range of values that the *RDPs* can take, the goal here is to determine the values of the *NRDPs* such that the range of system performance is maximized under the constraint that the performance is relatively insensitive to the variation of the *NRDPs*. Table 1 illustrates the partitioning principle for a generic microelectrofluidic system.

The organization of the paper is as follows. The general problem statement and design approach are presented in Section 2. We describe the Taguchi experiment design method [9], which is used to determine the value of the *NRDPs* for robust design. We also present the response surface methodology [7], which is used to maximize the performance range for a given programmable set of *RDPs*. Section 3 further describes the design procedure for achieving application flexibility. Section 4 presents a case study based on the microvalve, which serves as a case study for an electrostatic microfluidic device. Section 5 summarizes the main contributions of the reported work and discusses directions for future research in composite microsystem optimization.

2 Design Approach

The overall microsystem cost and performance are affected by the partitioning of the design parameters into *NRDPs* and *RDPs*. The partitioning decision depends on the relationship between design parameters, system reliability and cost. Some of the issues influencing the partitioning decision are as follows:

¹This work is supported in part by DARPA under contract F30602-98-2-0140.

Table 1: Design parameters for a microfluidic system.

Abstraction Level	Nonreconfigurable Design Parameters (<i>Hardware</i>)	Reconfigurable Design Parameters (<i>Software</i>)
System	Number of I/O Interface Ports Number of Delivery Channel Buses	Plug in/out Strategy Process Scheduling
Component	Beam Dimension	Pressure
	Channels Diameter	Electrical Voltage
	Fabrication Materials	Operating Frequency

- *Correlation*

Correlated parameters must be placed in the same category. For example, there is significant correlation between the beam width and the perimeter of the moving electrode in the accelerometers [6]. Therefore, these two parameters (beam width and perimeter of electrode) must be placed in the same category.

- *Ease of control*

Some design parameters, e.g. fluid pressure and electrical voltage, are relatively easy to control during operation. Therefore, these can be placed in the *RDP* set to increase application flexibility.

- *Cost*

The cost of reconfiguration can also be a driving factor. For example, geometric parameters are expensive to alter after fabrication. Hence these are preferably placed in the *NRDP* set to reduce cost.

The *NRDP* value are determined at manufacturing time, and this provides a nonreconfigurable “hardware” platform. The *RDPs* constitute the “re-programmable software” that run on this platform. In this way, composite microsystems provide design flexibility for product evolution and different application purposes.

One of the system optimization objectives is to find an optimal setting of the *NRDPs* that makes the system performance less sensitive to the fluctuation of the manufacturing process and the operating environment. The Taguchi parameter design method, which is widely used for off-line parametric optimization control and high reliability design [9], is used here to achieve this objective.

By choosing levels of the design parameters, we can make the system performance less sensitive to variation of the set of noise factors. Performance variability is computed using a statistical metric signal-to-noise ratio (*SNR*). System performance is considered a “signal” and parametric fluctuations are considered “noise”. Our performance variability reduction method computes the effect of each setting of design parameters on *SNR* and uses the comparison results to determine the best combination of parameter settings to optimize performance stability [3].

The next design objective is to determine the degree of “programmability” of the *RDPs*. The following factors must be considered in this context:

- *Microsystem energy requirement*

The energy supply available for composite microsystems is limited due to miniaturization and integration. Hence, the energy requirement of the *RDPs* must conform to this restriction. For example, the adjustable range of the electrical voltage must lie in the available voltage range.

- *Limitation of physical implementation*

The limitation of physical implementation is also a key for “programmability” of *RDPs*. For example, the operating frequency of a micropump chamber may be limited by the feasibility of physical implementation.

- *Fabrication technology and integration level*

As composite microsystems become smaller, the fabrication technology and integration levels also limit the range of *RDPs*.

- *Operational reliability*

Higher degree of “programmability” of *RDPs* may lead to operational reliability problems, hence it may be more difficult to maintain the accurate control at a wider range.

Next, based on an appropriate setting of the *NRDPs* and the determined programmability of *RDPs*, the composite microsystem performance flexibility can be obtained. Since the degree of programmability of the *RDPs* is usually limited, we assume that the relationship between *RDPs* and system response is a unimodal function. This implies that on the system response surface, there is exactly one point possessing the minimum performance value and exactly one point possessing the maximum performance value, as shown in Figure 1. Therefore, the local optimal design point is also the global optimal design point in this design space.

In order to manage computational complexity, we use iterative search algorithms to determine an optimal design point. When there is just one *RDP*, the relationship between system performance and the *RDP*

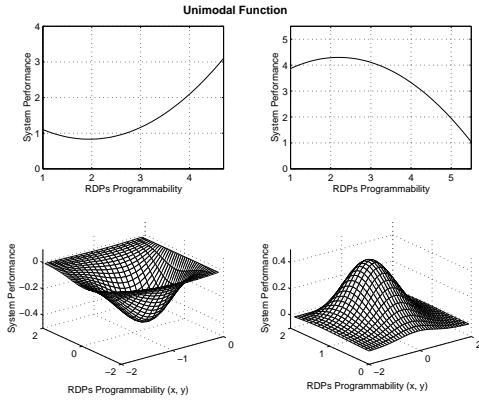


Figure 1: Unimodal function for two-dimensions and for higher-dimensions.

can be represented with a curve in the X-Y plane, and a one-dimensional iterative search method, such as *Golden section*, or *Fibonacci* search method can be used to find the minimum and maximum performance points [8]. If the number of *RDPs* is greater than one, the response surface method can be used to represent the relationship between system performance and the *RDPs*. An iterative gradient search method, such as *Steepest ascent/descent* [7], can be used to find the optimal points.

3 Optimization Procedure

The objective of *NRDPs/RDPs* co-design is to obtain a wider system performance within the feasible programmability range of the *RDPs* and a robust setting of the nonreconfigurable “hardware” platform. Since this optimization problem involves multiple objectives, designers need to trade off each objective to get an appropriate design result. Therefore, the optimization procedure includes four steps:

1. Depending on the partitioning criteria, the design parameters are grouped into *RDP* and *NRDP* sets.
2. Select a series of settings for the *NRDPs*—the “hardware” platform.
3. Using an iterative search algorithm, the minimum and maximum performance values are found within the determined programmability of *RDPs*.
4. The system robustness (insensitivity to *NRDPs*) is represented using *SNR* and optimized using the Taguchi robust design methodology. Since the *SNR* value for a certain setting of the *NRDPs* also depends on the setting of the *RDPs* within the programmability range of *RDPs*, the *SNR* for this setting of *NRDPs* may be different with the individual value of *RDPs*. However, with the unimodal assumption, it is reasonable to assume that

the robustness for a certain setting of *NRDPs* is equal to the average of *SNRs* which are calculated at the *RDP* nominal setting value, and the *RDP* values corresponding to the minimum and maximum performance values.

4 Case Study: Microvalve Modeling and Optimal Design

In this section, we present a case study for an electrostatic microfluidic device, the microvalve. A microvalve behavior model is developed using the hardware description language, VHDL-AMS. The final optimized design result ensures robustness and a wider performance range for application flexibility.

4.1 Microvalve Modeling

The pressure-driven check valves significantly affect the behavior of the micropump since it determines the micropump flow rate. The major parts of the check valve are a cantilever beam and valve seats. Normally the cantilever lies against the valve seat, thereby closing the port to fluid flow. During operation, the fluid flow exerts the pressure against the cantilever. The cantilever, acting like a spring, deflects and allows the fluid to flow through the valve. The schematic view of the open valve is shown in Figure 2 [10].

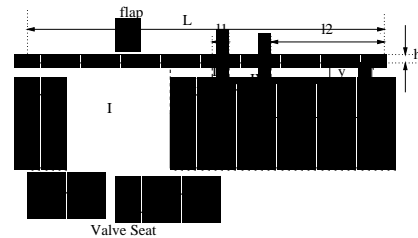


Figure 2: Schematic view of the open valve of a micropump.

The behavior of the cantilever can be described by a second-order differential equation,

$$m\ddot{y} + d\dot{y} + ky = pA \quad (1)$$

where y is the the displacement of cantilever beam, m is effective mass of the cantilever, including the mass of the cantilever and that of the liquid surrounding the cantilever, d is the damping constant, determined by the geometry of the cantilever. The spring constant k can be determined by FEM simulation or analytical results. p is the actuated pressure difference, and A is the area within the valve seat.

To obtain the flow rate Φ , the gap between the cantilever and the valve seat is divided into five pieces (Figure 2). By studying the effect of the pressure difference

p in the individual regions and the displacement of the cantilever beam, the overall flow rate Φ is completely determined by the actuated pressure difference p and the structural parameters. We use VHDL-AMS, an analog hardware description language, and an analog solver, Saber, to build and simulate this non-electrical model.

4.2 Optimal Design

Depending on the physical principles of the microvalve and the partitioning criteria, the design parameters can be grouped into the *NRDPs* and *RDPs* sets. The geometric design parameters are grouped into the set of *NRDPs*, and the pressure difference P_a is placed in the *RDP* set. The partitioning is shown in Table 2, where L is the length of the cantilever, b' is the width of the cantilever, h' is the thickness of the cantilever, h is the height of the valve seat, l_1 is the length of the valve seat, b is the width of the valve seat, l_2 is the length of the cantilever over valve seat, and E is Young's Modulus.

Table 2: *NRDPs* and *RDPs*.

<i>NRDPs</i>	<i>RDPs</i>
$L, b', h', h, l_1, b, l_2, E$	P_a

Our design objectives is to minimize the variation of the overall flow rate Φ due to the fluctuation of design parameters. Here, we assume that the design parameter tolerances are $\pm 0.2\mu m$.

To determine the *NRDP* settings for robust design, we use the three design levels for each *NRDP* as shown in Table 3. Since the fabrication material is always silicon, the Young Modulus E equals $146.9GPa$. In addition, the *RDP* (pressure difference P_a) is assumed to be a sinusoidal pressure at a frequency of 100Hz. The amplitude of P_a is limited in the range of 5,000 to 15,000 Pa , the nominal design setting value is set to 10,000 Pa .

Table 3: Design levels for *NRDPs* (units: μm).

<i>NRDPs</i>	L	b'	h'	h	l_1	b	l_2
(-)	1280	800	12	40	4	320	80
Level (0)	1600	1000	15	50	5	400	100
(+)	1920	1200	18	60	6	480	120

Considering the limited interaction between the parameters, a $1/3^p$ fraction of the original orthogonal array is used for experimental designs with reduced $O(3^{(n-p)})$ complexity, where, n is the number of *NRDPs*. Each *NRDP* is assumed to have three levels, and p is related to the order of interactions. Depending on the composite microsystem characteristics, we use the orthogonal array L_{243} with three levels for *NRDPs* setting to di-

rectly evaluate the contribution of individual parameters to overall design robustness [7].

Using the one-dimensional iterative *Fibonacci search* method, the setting points of P_a corresponding to the minimum flow rate and the maximum flow rate are obtained for each *NRDP* setting. Next, the average robustness corresponding to the settings of nonreconfigurable "hardware" platform is obtained. Figures 3 and 4, and Tables 4 and 5 present the microvalve robustness and flowrate range for different *NRDP* settings. For example, regardless of other design parameter settings, system robustness, *SNR*, with L setting at lower level ($1280\mu m$) is 66.67, and the system flowrate range $\Delta\Phi$ is $218.26\mu l/min$. Figure 5 and Table 6 present the optimal design results: the setting with $L_{(+1)}, b'_{(+1)}, h'_{(0)}, h_{(+1)}, l1_{(+1)}, b_{(+1)}, l2_{(+1)}$ possesses the widest flowrate range, and the setting with $L_{(-1)}, b'_{(+1)}, h'_{(+1)}, h_{(0)}, l1_{(0)}, b_{(+1)}, l2_{(-1)}$ possesses the best robustness. In addition, Figures 3 and 4 also directly provide very useful information for related performance improvement. For example, increasing the value of L, b' and b increases the range of flow rate, while decreasing the value of L and increasing the value of b improves microvalve robustness.

Table 4: Average *SNR* ratio for the design parameters.

Parameter	Average <i>SNR</i> * by level		
	lower (-1)	normal (0)	high (+1)
L	66.67	65.90	64.95
b'	65.42	65.67	66.43
h'	64.26	66.36	66.90
h	65.86	65.87	65.79
l_1	65.85	65.85	65.82
b	64.47	65.97	67.08
l_2	65.86	65.84	65.83

Table 5: Flowrate range $\Delta\Phi$ [$\mu l/min$]for the design parameters.

Parameter	$\Delta\Phi = \Phi_{max} - \Phi_{min}$ by level		
	lower (-1)	normal (0)	high (+1)
L	218.26	272.64	326.58
b'	218.54	272.53	326.42
h'	272.50	272.80	272.18
h	272.42	272.49	272.57
l_1	272.47	272.50	272.51
b	217.83	272.47	327.18
l_2	272.33	272.49	272.66

5 Conclusions

We have leveraged the principles of the hardware/software co-design methodology to develop a novel design approach for enhancing the application flexibility of com-

Table 6: Design results.

	L	b'	h'	h	l_1	b	l_2	Minimum Φ	Maximum Φ	Range ($\Delta\Phi$)	(SNR)
Nominal Design	1600	1000	15	50	5	400	100	64.75	337.61	272.86	66.66
Most Robust	1280	1200	18	50	5	480	80	73.44	387.44	314.00	69.13
Widest Range	1920	1200	15	60	6	480	120	112.53	582.39	469.86	63.45

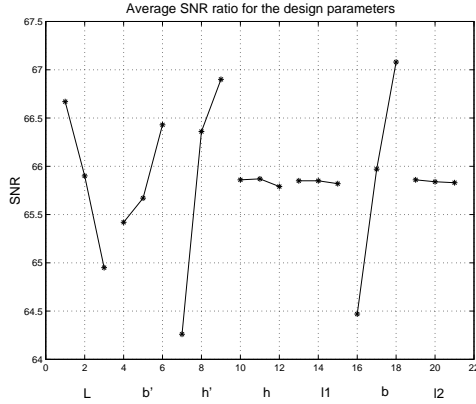


Figure 3: Plot of design parameter effect on SNR.

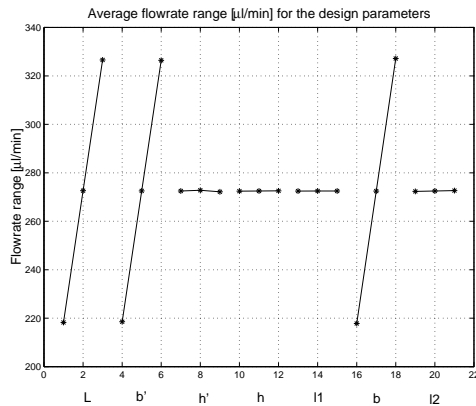


Figure 4: Plot of design parameter effect on flow rate range

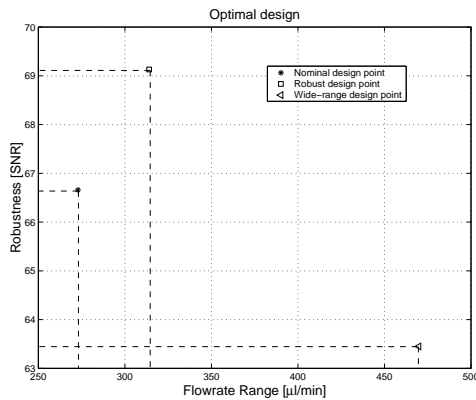


Figure 5: Plot of optimal design points.

posite microsystems. This methodology is also useful for rapid prototyping and CAD tool development. We are currently extending the proposed co-design approach to higher-level design optimization, including system architecture and performance evaluation.

6 Acknowledgment

The authors acknowledge the contributions of F. Cao in the development of the microvalve simulation model.

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