Proceedings of the 7th IEEE
International Conference on Nanotechnology
August 2 - 5, 2007, Hong Kong

A Novel Design Methodology for MEMS Device

Xin Zhao, Lei Wang*, Yiyong Tan, Guangyi Sun and Guizhang Lu

Institute of Robotics and Automatic Information System, Nankai University, Tianjin 300071, China

***Abstract*—Due to MEMS device needs highly accurate design, a novel design methodology for MEMS device is put forward in this paper. Firstly, top-down and bottom-up hybrid design process based on IP library is proposed. It facilitates and speeds up design cycle and reduces the expense of MEMS design by using IP components which have been successfully implemented. Secondly, Virtual Fabrication Process is proposed. It is used to establish stable, accurate and robust 3D geometry of device according to the fabrication process. Voxel-based visualization technique is applied to Virtual Fabrication Process to achieve better process simulation result. It could help designers achieve highly accurate fabrication process and result. Thirdly, Virtual Operation is proposed. It is used to visualize and simulate the mechanical operation of MEMS device. This module could exhibit 3D realistic animation in Virtual Reality (VR) environment. It could help designers achieve highly accurate physical operation characteristic of MEMS device. With the help of Virtual Fabrication Process and Virtual Operation, intuitive image and realistic animation of MEMS device is exhibited at the design stage. An available prototyping MEMS CAD which implements both top-down and bottom-up design notion integrates with Virtual Fabrication Process and Virtual Operation. A bimetallic thermally-actuated micropump is studied through the paper using this novel design methodology.**

Keywords-MEMS; Microfluidic Device; IP library; Virtual Reality; Virtual Fabrication Process; Virtual Operation;

I. INTRODUCTION

As one of the most promising member of MEMS, microfluidic systems have found wide applications. Therefore, they are getting more and more attractive for researchers in the field of MEMS [1]. Microfluidic system needs highly accurate design which leads to the following issues in its design process. Firstly, it is a better choice to reuse the successfully designed and implemented microfluidic components such as microvalves, micropumps and so on. Secondly, in order to achieve highly accurate design result, it is important to get accurate fabrication process and results before carrying out the physical fabrication process. Thirdly, to achieve highly accurate operation result, it is necessary to preview the dynamic operation statement during the design stage.

There are a few commercial MEMS design tools are available currently, however these design tools have their limitations. Some of them are not specifically for MEMS, and others are only for specific phases in the MEMS design and development. The leading Computer-Aided Design (CAD) tools in MEMS industry include MEMS PRO [2], ConventorWare [3], IntelliSuite [4], ANSYS [5], CFD-VIEW [6]. However their application is primarily to determine the MEMS manufacturing parameters. The availability of Virtual Reality in this area appears but is limited to very few software packages [7]. A novel MEMS design methodology combined with top-down and bottom-up conceptions is put forward in this paper. Besides, Virtual Fabrication Process [8] and Virtual Operation [9] are also utilized in the design process which could exhibit 3D realistic image and real-time animation of microfluidic device. IP (Intellectual Property) library is established to support hybrid top-down and bottom-up design notions. Also an integrated MEMS CAD composed of these design ideas is developed.

The design process of bimetallic thermally-actuated micropump is studied throughout the paper. The micropump discussed in this paper is developed at Tsinghua University. It is redesigned using top-down and bottom-up hybrid design method. Good simulation results are achieved in Virtual Fabrication Process and Virtual Operation modules integrated in our prototyping MEMS CAD.

II. A NOVEL DESIGN METHODOLOGY FOR MICROFLUIDIC DEVICE

A. General Design Process for Microfluidic Device

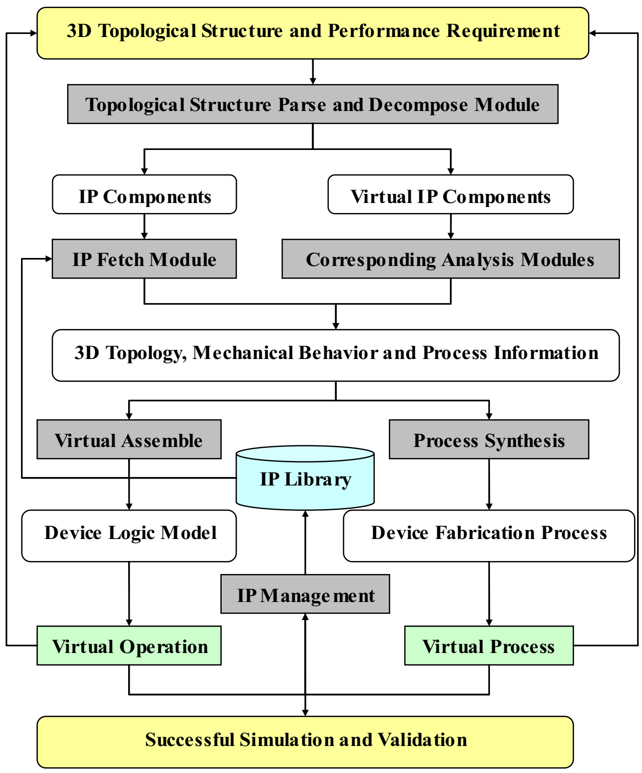


Fig.1. Architecture of MEMS design system with top-down and bottom-up hybrid design methodology based on VR technology

This project was funded by the Chinese National 863 Plan (Project code: 2006AA04Z304)， the National Science Foundation of China (Project code: 60674068)

**Contact author: Lei Wang， phone: +86-22-23508296-8005; email: wanglei@robot.nankai.edu.cn.*

A novel design process which combines top-down and bottom-up [10] design method is proposed. The hybrid design process is supported by an IP (Intellectual Property) library. At the beginning of design flow, any microfluidic device divides into pieces of components. All divided components can be classified into two categories-IP components (IP) and virtual IP components (VIP). IP is the components stored in the IP library which contains a variety of successfully verified and fabricated cases, while VIP is the components which excludes from the IP library. For IP derived from the components library (IP library), 3D geometry, kinematical or dynamical mechanical rules, mask and process information, etc, are directly acquired from the library. In contrast, VIP is kinds of the component which have not been developed. Designer should design and simulate from origin. Information about 3D geometry, mechanical performance and fabrication process is produced using corresponding analytical modules.

After decomposition analysis process, available IP from IP library and VIP designed originally can be achieved. This indicates the top-down conception in design process. Then bottom-up design process is carried out. This is implemented through the assembly and synthesis from IP and VIP information. Virtual Assembly and Process Synthesis modules in our CAD system are used to assemble or synthesis the components information. Logic Device model including 3D geometry and mechanical characteristic generated from Virtual Assembly module is imported into Virtual Operation to carry out mechanical behavior simulation. At the same time, mask and process information acquired from Process Synthesis module is input into Virtual Fabrication Process to achieve more realistic 3D geometry using specific fabrication process. Fig.1 shows the basic system architecture including top-down and bottom-up hybrid design process.

The advantage of using hybrid design methodology is to adequately reuse the resource and information stored in IP library. With the aid of successfully implemented design experience which acquired from IP library, design cycle and costs will decrease largely. More available components in the library, more efficient and effective design process can be achieved. With more and more successfully designed and fabricated MEMS have been added to IP library, this kind of design approach could release more energy.

B. Design Process of Thermally-Actuated Micropump

The bimetallic thermally-actuated micropump [11] is developed at Tsinghua University. The basic structure of micropump is shown in Fig.2.

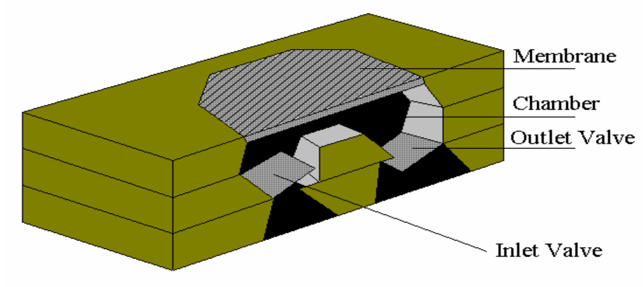


Fig.2. Basic structure of thermal micropump

This thermally-actuated micropump is composed of a bimetallic actuated membrane, one chamber and two micro check valves. Microactuators and microvalves are the main parts of micropump. For this case, it is made up of 10 μm aluminum and 20 μm silicon chips. The size of bimetallic membrane is $4500\mu m \times 4500\mu m$. Due to different magnitude of coefficient of thermal expansion between two different materials, the membrane is intended to bend down and up corresponding to the temperature variation.

The micropump could be divided into four pieces including bimetallic membrane, inlet cantilever microvalve, outlet cantilever microvalve and chamber. Assuming cantilever beam has been implemented and added to IP library. So inlet cantilever microvalve and outlet cantilever microvalve is classified as IP, while the other components is classified as VIP which will simulate and design using corresponding analytical tools. Fig.3. shows IPs and VIPs divided from thermal micropump.

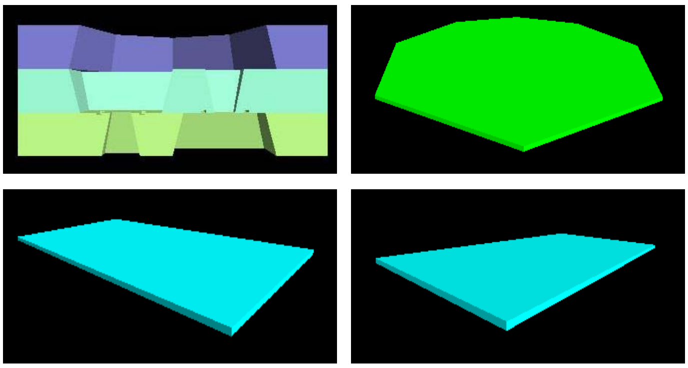


Fig.3. IP and VIP divided from bimetallic thermally-actuated micropump

Decomposition process of micropump has been carried out to generate necessary components including IP and VIP. This operation illustrates top-down design process in hybrid design methodology. All divided components contain information about 3D geometry, dynamic or kinematic mechanical behavior and fabrication process, etc. After that, bottom-up design process can be carried out through Virtual Assembly and Process Synthesis modules. Virtual Assembly operation is required to assemble all the components to set up the logic model of micropump. Fig.4. illustrates the Virtual Assembly results of micropump including mechanical behavior besides 3D topology.

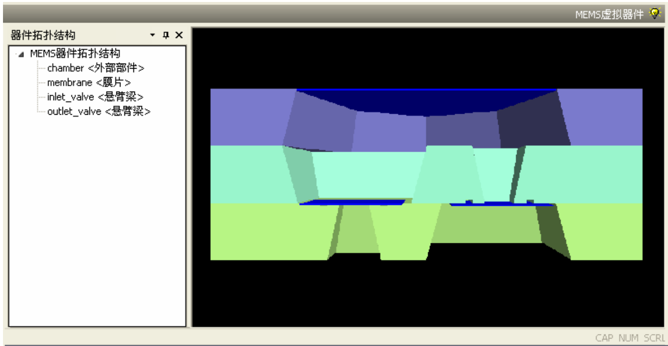


Fig.4. Virtual Assembly results for bimetallic thermal micropump

III. VIRTUAL FABRICATION PROCESS FOR MICROFLUIDIC DEVICE

A. Basic Principle of Virtual Fabrication Process

The traditional approach using a solid geometry kernel can only perform ideal simulation, describes device in simple topology. To overcome those problems, the paper puts forward a approach based on voxel-based modeling and rendering.

There are three crucial parts in the implementation of Virtual Fabrication Process: automatic multistep simulation, volume data computation and volume data visualization. Automatic multistep simulation had been implemented by inference engine based on expert system in our previous work. In the second part, we use 3D mathematical morphology operations of conditional dilation and erosion to construct voxel-based representation of MEMS device. At last, visualization is implemented by using direct volume rendering techniques. The basic framework of Virtual Fabrication Process is proposed in Fig.5.

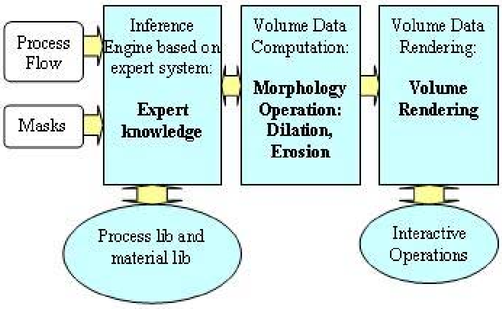


Fig.5. Basic framework of Virtual Fabrication Process

Mathematical Morphology is utilized in the operation of voxel set which indicate spatial and topological information of device. According to different mask and process information, three-dimensional morphology operation is carried out to form inner representation of device geometry.

B. Virtual Fabrication Process for Bimetallic Micropump

As inputs, fabrication process and masks of microvalves and bimetallic membrane are listed in TABLE1 and TABLE2. These inputs will be converted into abstract data by inference engine. The voxel-based geometry is then built in a layer by layer fashion by simulating the processing steps used to build the actual device.

TABLE 1 FABRICATION PROCESS FLOW OF MICROVALVE

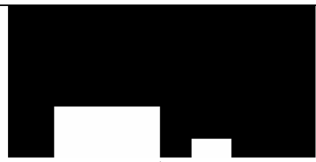
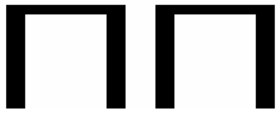
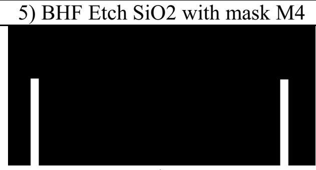
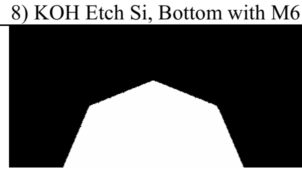
1) KOH Etch Si, M1, Top KOH anisotropic etch on top of Si wafer with mask M1	2) KOH Etch Si, M2, Bottom KOH anisotropic etch on bottom of Si wafer with mask M2
 Mask M1	 Mask M2

TABLE 2 FABRICATION PROCESS FLOW OF MEMBRANE

1) Deposit SiO2	2) Deposit Si3N4
3) RIE Etch Si3N4 with mask M3	4) Deposit SiO2, LPCVD
 Mask M3	N/A
5) BHF Etch SiO2 with mask M4	6) Vapor Al
 Mask M4	N/A
7) Lithography Etch Al with M5	8) KOH Etch Si, Bottom with M6
 Mask M5	 Mask M6

Through Virtual Fabrication Process, step simulation results of physical fabrication can be gotten and demonstrated in Fig.6 and Fig.7. Fig.6 shows the process of microvalves and Fig.7 shows the process of membrane. The final results of Virtual Fabrication Process are shown in Fig.8.

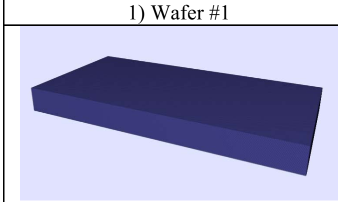
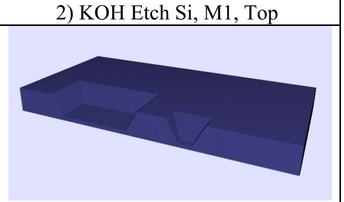
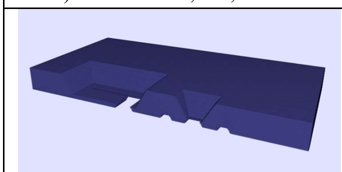
1) Wafer #1	2) KOH Etch Si, M1, Top
	
3) KOH Etch Si, M2, Bottom	
	

Fig.6. Virtual fabrication process of microvalves

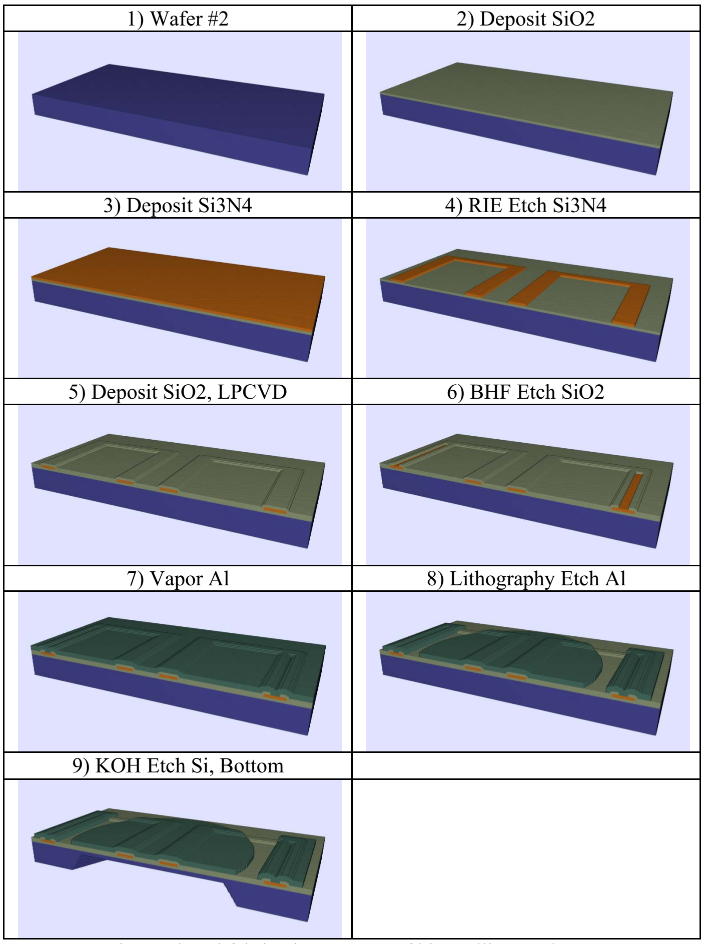


Fig.7. Virtual fabrication process of bimetallic membrane

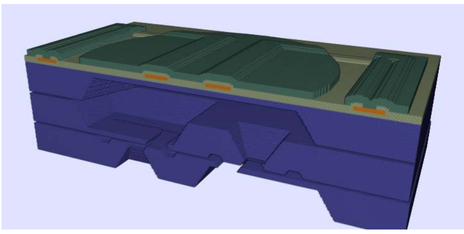


Fig.8. Cross-section view of final simulation result

With the simulation of fabrication process, designers could preview 3D geometry of microfluidic device in design stage. Moreover, it provides assistant in optimizing design and achieving highly accurate design result.

IV. Virtual Operation For Microfluidic Device

Virtual Operation establishes direct relationship between device mechanical characteristics and design parameters. It could exhibit 3D dynamic animation of MEMS device's mechanical behaviors and make designers watch operation state of the device in real-time.

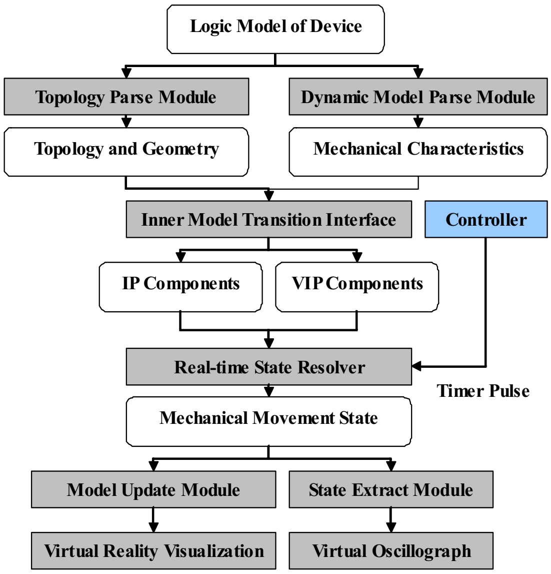


Fig.9. Basic framework of Virtual Operation

As shown in Fig.9, Virtual Operation consists of four key functional modules including Operation Controller, Real-time Mechanical State Resolver, Model Update and State Extract Module and Visualization Modules. With periodic pulse released from the central controller, the real-time mechanical state of device is calculated and updated correspondingly. By using Virtual Reality technology, more realistic dynamic animation could be exhibited during the simulation process.

It is often difficult to construct accurate models for MEMS devices using traditional method just as lumped-parameter techniques [12], especially when arbitrary geometries are involved. The paper proposed a numerical modeling approach using Finite Element Method (FEM) [13] computation.

A. General Modeling Approach

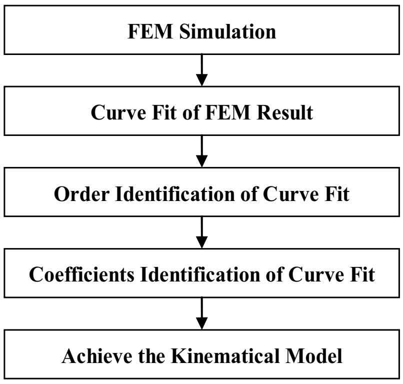


Fig.10. Basic modeling procedure of MEMS device using FEM simulation for virtual operation

This modeling procedure (Fig.10) could be easily extended to various complicated MEMS device involving multiphysics problems.

B. Modeling Process of Micropump

The modeling process of bimetallic thermally-actuated membrane in micropump is illustrated. Due to the membrane is related to the thermal and mechanical issues, it is much more appropriate to generate the dynamic model using FEM modeling process introduced above.

1. Carry out linear static FEM computation. The FEM result is discrete nodal information which describes the deformation shape of membrane. Fig.11. shows the FEM analysis result at temperature 100 ℃.

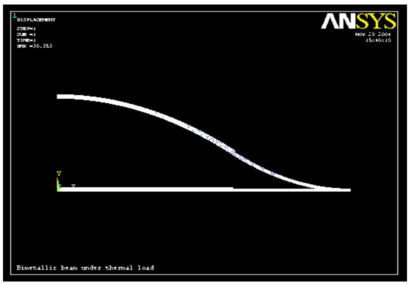


Fig.11. FEM simulation result of membrane

2. Order Identification of polynomial fit expression should be confirmed first to carry out other steps in the modeling procedure. Fig.12. shows the comparison among the fit results with different orders.

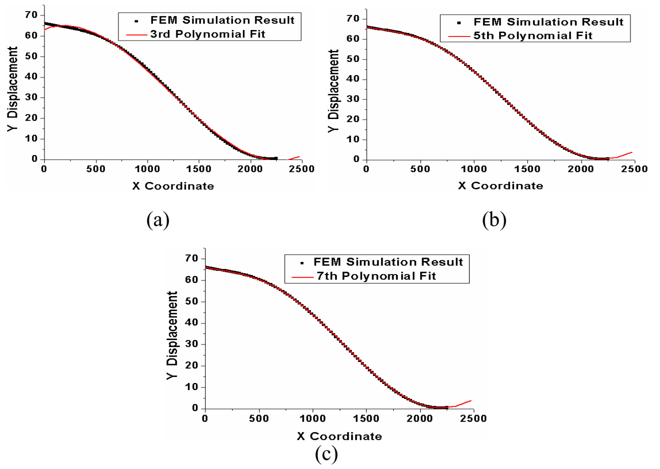


Fig.12. Polynomial fit results with different orders

3. Parameter identification of polynomial fit expression is required after order identification operation. Fig.13 shows the FEM simulation results and polynomial fit for different increment of temperature.

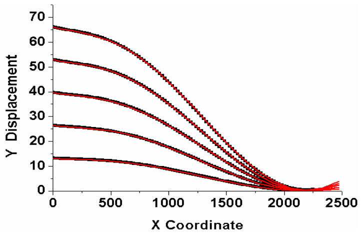


Fig.13. FEM simulation results and polynomial fit for different conditions

All coefficients in polynomial for various conditions have been listed in Table 3.

TABLE 3 COEFFICIENTS IN POLYNOMIAL FOR DIFFERENT INCREAMENT OF TEMPERATURE (20℃, 40℃, 60℃, 80℃, 100℃)

Temp	B0	B1	B2	B3	B4	B5	Adj.
20℃	13.25	-0.00248	4.89E-6	1.23E-8	6.25E-12	-9.11E-16	0.99981
40℃	26.53	-0.0048	9.04E-6	-2.52E-8	1.26E-11	-1.83E-15	0.99981
60℃	39.76	-0.00688	1.34E-5	-3.49E-8	1.75E-11	-2.49E-15	0.99984
80℃	53.03	-0.00941	1.82E-5	-4.6E-8	2.38E-11	-3.41E-15	0.99981
100℃	66.35	-0.01127	2.31E-5	-5.93E-8	3.07E-11	-4.27E-15	0.99981

Approximate linear relationship over each coefficient could be found in each column of Table 3. Linear fit for each polynomial coefficient has been carried out to verify the linear coefficient assumption.

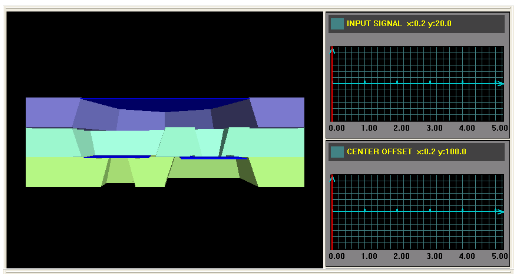
The linear function T_n could be generated from the linear fit expressions. It established the linear relationship between the polynomial fit coefficients and any time-dependent load. The relation between deformation of membrane and change of temperature could be acquired according to the preceding modeling approach.

$$\begin{aligned} & Y = \Delta T * S = \Delta T * \left(B_0 + B_1 X + B_2 X^2 + B_3 X^3 + B_4 X^4 + B_5 X^5\right) \\ & B0 = 0.66197, B1 = -1.143E-4, B2 = 2.226E-7, B3 = -5.807E-10 \\ & B4 = 2.918E-13, B5 = -4.145E-17 \end{aligned} \qquad (3)$$

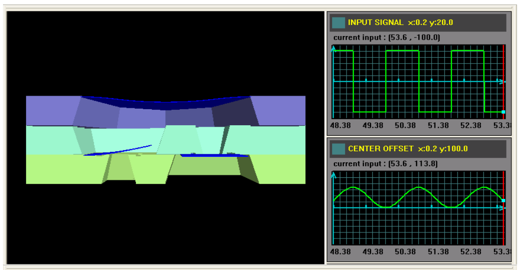
C. Virtual Operation Result

Virtual Operation of thermal micropump is shown in Fig.15. It could assist MEMS designers better understand the working principle of micropump. The cross-section view of micropump is illustrated in order to visualize inner operation state of bimetallic membrane and microvalves.

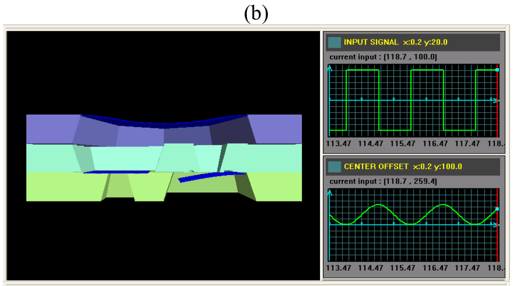
The left view in Fig.14 demonstrates the real-time mechanical operation of bimetallic thermally-actuated micropump using VR technology. The right-top view shows the driving voltage of micropump. The right-bottom view shows the equilibrium position of the membrane depart s from the static position.



(a)



(b)



(c)

Fig.14. Virtual operation of micropump (cross-section view) (a) No operation (b) State of operation with inlet valve opening (c) State of operation with outlet valve opening

With the comparison between driving voltage and mechanical operation of micropump, critical design parameters such as the center position of membrane and so on, designers experience the physical operation of micropump. Moreover, designers can optimize the design of microfluidic device. Eventually, Virtual Operation provides assistant in designing and achieving highly accurate physical operation characteristic.

V. Conclusion

A novel design methodology for microfluidic device is proposed in this paper. A prototyping system involved new design methodology is also developed. The bimetallic thermally-actuated micropump is redesigned and certificated using the prototyping system.

Due to the establishment of IP library, it is possible to reuse successfully implemented components. Virtual Fabrication Process can be used to preview the fabrication process and result of microfluidic device, which make sure the design solution could be highly accurately fabricated. Virtual Operation can demonstrate physical operation state of microfluidic device, which make sure the design solution achieve the highly accurate operation characteristic.

This design methodology is suitable for MEMS device, especially for microfluidic device which needs highly accurate fabrication process and physical operation.

VI. Acknowledgement

Prof Litian Liu, institute of microelectronics, Tsinghua University, provided the material of bimetallic thermally actuated micropump. The authors thank for the help of Prof Liu.

VII. References

[1] Zhou Zhaoying, Feng Yanying, et al. "Studies on microfluidic systems and related topics", International Journal of Nonlinear Science and Numerical Simulation, 1, pp.437~444, 2000.

[2] MEMS PRO, MEMSCAP, Oakland, CA, USA.

[3] CoventorWare 2001.1, Coventor, Cary, NC, USA.

[4] IntelliSuite, IntelliSense Corporation, Wilmington, MA, USA.

[5] ANSYS/Multiphysics, ANSYS Inc., Canonsburg, PA, USA.

[6] CFD-VIEW, CFD Research Corporation, Huntsville, AL, USA.

[7] Z.Li, R.Sitte, "Virtual Reality Reality Modelling Aiding in MEMS Design", Proceedings of SPIE 2001 International Symposium on Microelectronics and Micro-Electro-Mechanical Systems, Electronics and Structures for MEMS, Adelaide, 2001.

[8] Xin Zhao, Yawei Li, Yiyun Zhou, Liang Ren, and Guizhang Lu, "Virtual Process: Concept, Problems and Implementation Framework," The Fourth International Conference on Control and Automation (ICCA'03), pp. 659-663, 10-12 June 2003, Montreal, Canada.

[9] Xin Zhao, Gui-zhang Lu, Xiang-dong An, "Virtual operations of two typical MEMS devices-Micromotor and Micropump," 14th world congress for IFAC, 1999.

[10] M. S. McCorquodale, F. H. Gebara, K. L. Kraver, E. D. Marsman, R. M. Senger, and R. B. Brown "A top-down microsystems design methodology and associated challenges", Proceedings of the Design,Automation and Test in Europe Conference and Exhibition, 2003.

[11] Zhi-zhong Yin, Jiang-tao Pang, Ning Xu, Li-tian Liu, Wei-lin Hu, Zeng-yuan Guo, Guan-chang Jing, "Experimental Study on Thermal Actuated Micropump ", Journal of Functional Materials and Devices, vol. 6, No. 2 .June ,2000.

[12] H. Tilmans, "Equivalent circuit representation of electromechanical transducers: I. lumped-parameter systems," *IEEE J. Electromicromech. Syst*., vol. 6, no. 1, pp. 157–176, Mar. 1996.

[13] J. Y. Qian, G. P. Li, F. de Flaviis, "Finite Element Model of Microelectromechanical Systems Switch Operating at Microwave Frequencies," *Electromagnetics.* vol. 22, no. 4, pp. 291-296, May. 2002.