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Intelligent Control of Piezoelectric Micropump Based on MEMS Flow Sensor

Liguo Chen, Yaxin Liu, Lining Sun, Dongsheng Qu, and Jijiang Min

Abstract—**The liquid dosing system has been studied widely as it had been used in many technical and medical applications. And in recent years, the miniaturization of the liquid dosing system as well as the accuracy of liquid transfer has gradually become a hot research field. In this paper, a MEMS (Micro-electromechanical system) flow sensor was integrated with a PZT(Piezoelectric Transducer) pump to make a closed-loop drug dosing system. Benefiting from the feedback of sensor information, the system can self-adjust the driving voltage of the PZT pump to precisely dispensing desired liquid volume. First, the structure and principle of the PZT pump will be introduced briefly. Secondly, the MEMS flow sensor is presented. Finally, the fuzzy PID (Proportional-Integral-Differential) closed-loop control strategy is proposed to calculate and adjust the driving voltage in real-time. Finally, experiment results show that the drug delivery system could precisely delivery drug volume with error smaller than 0.01µL when desired volume is 100µL.**

I. INTRODUCTION

Micropumps are the essential components in the liquid handling system, micro analytical instrumentation, genetic engineering, protein synthesis, portable sampling systems, environmental monitoring and drug delivery. A micro-pump (with integrated micro-valves) is a device that can provide a precise and controllable amount of fluid usually in the range of pl/min to ml/min. Recently, various mechanical micropumps with different actuating principles have been developed [1,2], such as thermopneumatic [3], electrostatic [4,5], shape memory alloy (SMA) [6-8], electromagnetic [9,10] as well as piezoelectric [11-16]. Most of them have complex structures and high power consumption. On the contrary, piezoelectric actuation has advantages of a relatively simple structure and lower power consumption. The piezoelectric actuation presents its advantages of moderately pressure and displacement at simultaneously low power consumption, good reliability and energy efficiency [11]. These features are preferred for medical application.

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Recently, the miniaturization of the liquid dosing system as well as the accuracy of liquid transfer has aroused more and more attention. There is an increasing demand for high precision pipetting of biological liquids (e.g. serum) and reagents in the micro- and submicroliter range. Precision pipetting means that controlled and precise aspirating and dispensing of a given volume.

While, because of the intrinsic behaviours of piezoelectric material like non-linearity, hysteresis and creep [17,18], piezoelectric micropumps can not be controlled precisely. If the precision of distributed reagent from a piezoelectric pump can not be improved, the application of piezoelectric pump must be greatly limited. Therefore, closed-loop-control of micropump through integrating sensors becomes more and more important.

Many micropumps and valves, mostly without sensors [19-23] except [24,25] have been reported. Nicolas Szita has realised an all-in-one device for aspiration and dispensing with integrated pressure and position sensors to obtain high precision and to monitor the whole pipetting process [26]. For this micropipette, using the signals of both sensors for closed-loop-control of the coupled actuator will eliminate the piezoactuator's hysteresis and drift and thus further increase precision and accuracy. Kamlesh D. Patel also integrated a pressure sensor into the quantificational supply system [27]. These works tried to adjust the pump flow rate through indirect control method, and can not directly measure and control the pump flow rate in real time. For those micropumps with integrated flow sensors [24,25], average flow rate was measured through the flow sensor. And no more control method was introduced to control the dosing volume precisely.

In this work, a MEMS flow sensor based on the measurement of pressure difference across a flow restriction was fabricated according to the characteristics of piezoelectric micropumps, and the closed-loop-control method was presented to control the dosing volume. The fast response time of the flow sensor make it suitable read the flow rate of pump quickly. With feedback flow information from the MEMS flow sensor, the micropump could self-adjust the driving voltage automatically so as to dosing the desired volumes.

II. THE PIEZOELECTRIC MICROPUMP SYSTEM

In this work, a MEMS flow sensor was fabricated and integrated into the closed-loop-control of piezoelectric miropump and the schematic structure of this system is shown in Fig.1.

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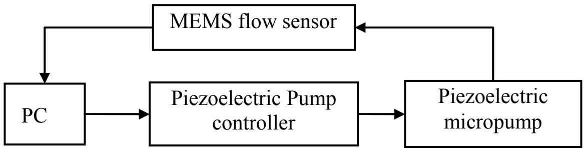
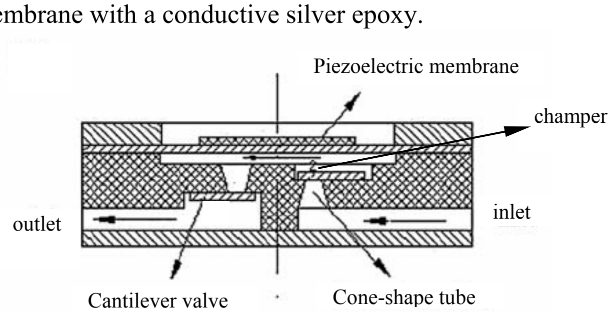


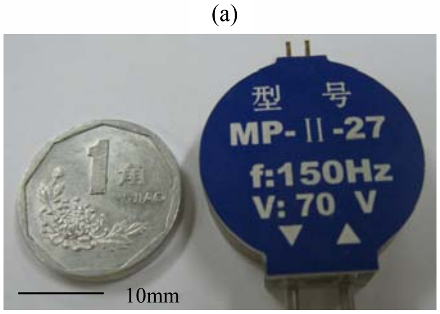
Fig.1 The schematic structure of the micropump system integrating MEMS flow sensor.

A. *Piezoelectric micropump*

The micropump is provided by prof. Zhigang Yang from Jilin University of China. The working principle of the PZT pump is shown in Fig. 2 a). It is a volumetric pump with a pumping membrane, which compresses the pumping chamber, an inlet, an outlet, and the check valves that direct the liquid flow. The disk membrane is a stack of three layers bonded together: a thin film membrane of piezoelectric material with micro machined pump structures is sandwiched between two brass shim stocks at the center. The piezoelectric element made from quartz, Li TaO_3, PZT or ZnO, has a thickness of 0.18 mm. It is bonded to the membrane with a conductive silver epoxy.



(a)



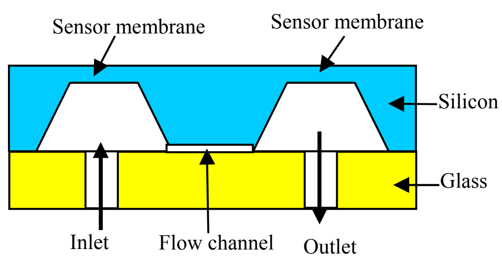
(b)

Fig.2 (a) The schematic structure of the PZT pump. (b) The photo of the Piezoelectric Pump.

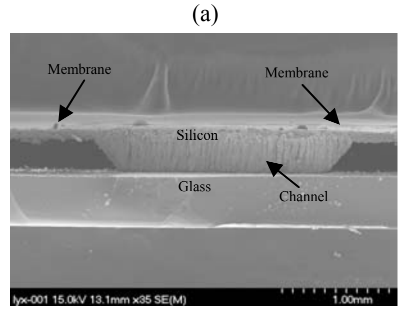
In piezoelectric pump actuation, a voltage is applied across the piezoelectric membrane, which then deforms, forcing the diaphragm to bend in order to actuate the flow of fluid. The flow direction of the liquid inside the chamber is based on the geometric design of the diffuser/ nozzle element to have a lower pressure loss in the diffuser direction than in the nozzle direction for the same fluid velocity. In supply mode where the membrane concaves up, the pressure inside the chamber decreases, the valve on the right opens, the valve on the left closes, and the fluid runs through the inlet into the chamber. In pump mode where the membrane concaves down, the pressure inside the chamber increases, the valve on the right closes, and the valve on the left opens, and the fluid flows out of the outlet, as shown in Fig. 2(a). And the photo of the PZT pump is shown in Fig.2 (b).The diameter of the PZT pump is Φ27mm, the maximum backside pressure is 35kPa.

B. *MEMS flow sensor*

In the pump dosing system, an integrated MEMS flow sensor based on the measurement of pressure difference across a flow channel is presented. The layout of the sensor chip is shown as Fig.3 (a). The sensor chip consists of two piezo-resistive sensor dies and a micro-machined channel. The dimensions of the two silicon cup membranes and the micro-flow channel are the key factors affecting the characteristic of the flow sensor. The size of silicon membranes should be designed properly to ensure that the membrane should not be broken at the maximum backside pressure of the PZT pump, and the deflection of the membrane should be within the range of linear elasticity. Generally, if the maximum center deflection of the membrane is smaller than half of the membrane thickness, the deformation can be considered as elastic deformation. Considering the micro channel, the size of the channel should be designed properly to ensure that the pressure drop across the channel is smaller than 25kPa. Based on the principles above, the sensor prototype was designed. It consists of two square silicon membranes with dimensions of 50 μm thick × 2,000 μm wide × 2,000 μm long, and the channel is designed as 2,005 μm long, 1000 μm width and 30 μm deep. The whole size of the sensor chip is 4.5mm ×9.0mm ×0.9mm. A SEM picture of cross-section of the sensor chip is shown in Fig.3 (b).



(a)



(b)

Fig.3 (a) The layout of the sensor chip. (b)The SEM picture of the sensor chip cross-section .

The sensor fabrication consists of an industrial piezo-resistive process with the addition of an extra back side anisotropic etch step to integrate the flow channel. We started the fabrication process in 400 μm-thick (100) oriented silicon wafers. The process flow is sketched in Fig.4 and described as follows: (1) The sensor was fabricated using a 4-inch, (100) orientation double polished silicon wafer with a thickness of 400μm. 0.5μm thick thermal oxide layer is grown on both sides of the wafer which is used as the protection layer for the boron infusion.

(2) The piezoresistive Wheatstone bridge regions are patterned by photolithography on the front side of the wafer and buffered HF etching. Then the remaining oxide layer under the photoresist and the photoresist formed the mask for next process. The piezoresistors were formed by boron ion implantation in the regions. Then, a drive-in process was done to activate boron ions in the Si.(3) The membranes and the channel are anisotropic etched using double mask technique. The SiO2 is deposited on the silicon substrate followed by a deposition of LPCVD Si3N4 on the oxide layer. Then the same deposition process is performed again. The membranes were patterned by photolithography on the backside of the wafer. The double masks SiO2 and Si3N4 on membranes areas were etched and the single masks SiO2 and Si3N4 on channel areas were etched away. (4) Then, backside etching process to form membranes was performed in KOH. (5) In order to reveal the channel pattern on the silicon substrate, the masks SiO2 and Si3N4 were etched once more. (6) Then channel and the membranes remained were etched in KOH.(7) The contact holes are patterned by photolithography and opened by wet etching in buffered HF solution. 0.8 μm-thick aluminum is sputtered.(8) Aluminum wires and bonding pads were formed by vacuum evaporation, photolithography, and etching processes.(9) Ultrasonic drilling is used to machining the holes on glass wafer. Then the glass wafer and silicon wafer were bonded together to form the support base and the channel.

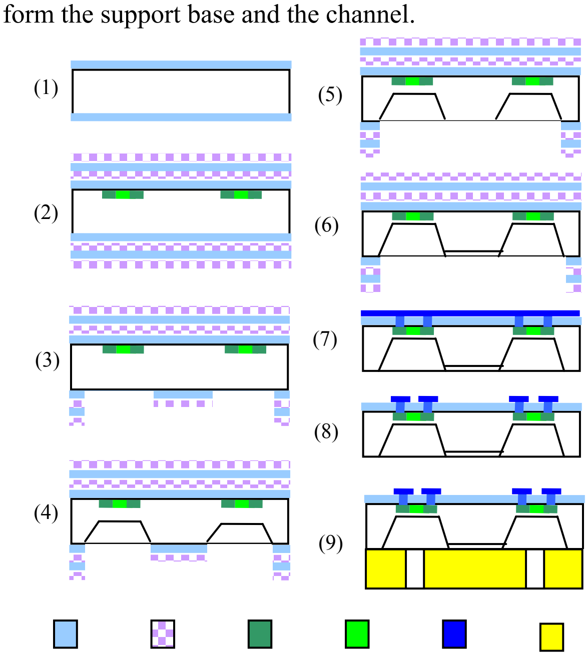
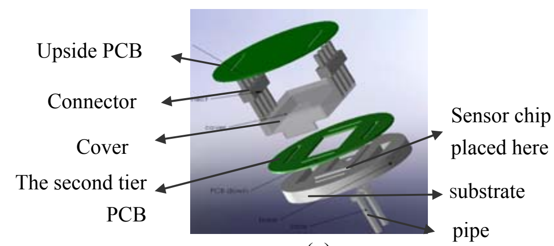


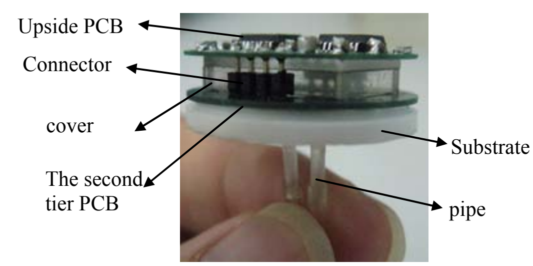
Fig.4 Process sequences of the pressure/flow-sensor chip.

The finished sensor chip was then mounted on a ceramic substrate and compensating electrical circuits and fluidic connections are all made on it. In order to integrate with the PZT pump to make a compact size delivery system, the sensor's shape is designed to cylindrical, and the diameter of it is the same as the PZT pump's (Φ27mm). The whole sensor's height is 11mm. The Fig. 5 (a) presents the schematic of the packaging configuration, and Fig. 5 (b) shows the photo of the sensor packaging configuration.

Outputs of sensor chip are magnified by two signal-conditioner Ics (MAX1452 from Maxim Company). Before being used, the sensor is connected to the communication module for pressure calibration. The calibrated maximum output under pressures(35kPa) is 4.5V. Then, The flow-voltage calibration is carried out using a syringe pump. The liquid used in the calibration experiment is pure water. The syringe pump can supply flow rates ranging from 0.4167 μL/s up to 40 μL/s. For each flow condition, the corresponding average output voltage was recorded. The output voltage differences for different flow rate are shown in Fig.6, where the sensitivity of the calibrated sensor is 100 mV/(μL/s). Based on the deviation between calibration curve and the fitting curve, the nonlinearity of flow sensor can be calculated as 0.51%.



(a)



(b)

Fig5 (a) The schematic of flow sensor packaging. (b)The photo of flow sensor .

The pressure difference flow sensor have fast response feature. And sensor response voltage signal corresponds to the flow rate switched to the stable status in 4ms after the open action of the pipe valve, which can be read by an oscillograph. It indicates that the sensor response time is shorter than 4ms. The fast response feature makes it possible to dynamic measurement of the sensor response of the pump.

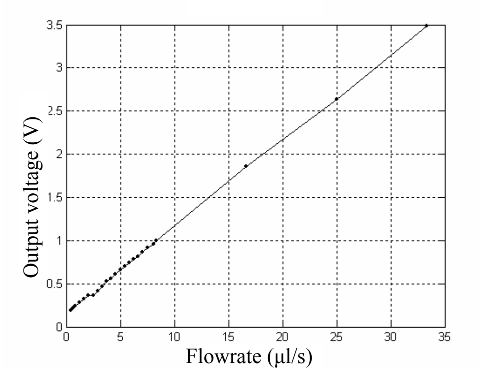


Fig.6 Sensor voltage output for different flow rate.

III. INTELLIGENT CONTROL

In most liquid dosing application conditions, the dosing volume needs to be controlled precisely, such as micro analytical instrumentation, genetic engineering and drug delivery and so on. So the flow sensor was integrated to make a closed-loop drug dosing system. Benefiting from the feedback of sensor information, the system can self-adjust the driving voltage of the PZT pump to precisely dispensing desired liquid volume. Look at Fig.7, it shows the experimental set of the pump based liquid dosing system.

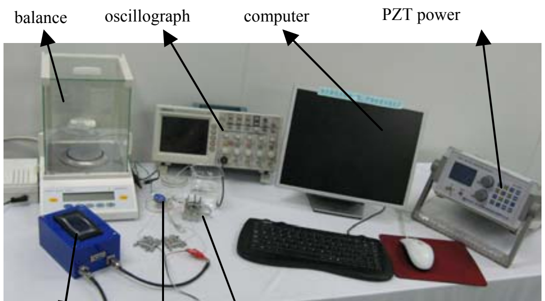


Fig.7 The photo of the PZT pump based dosing system.

During the experiment, in order to replace pump or flow sensor more conveniently, soft tubes are used to connect the pump outlet and inlet of the flow sensor. And the inlet of the pump is immerged in the water that filled in the beaker. It is convenient to replace pump or flow sensor. Besides read the flow rate date through computer, a flow rate display module and oscillograph are also used to observe the voltage across the PZT pump and the real-time flow rate.

Fig.8 shows the real-time flow rate curve when driving voltage amplitude of the PZT pump is 30V and the frequency is 20Hz.

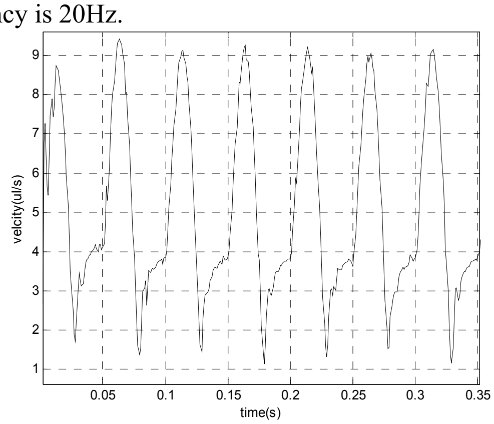


Fig.8 Flow rate of the pump vs. time (pump driving voltage amplitude is 30V and frequency is 20Hz).

From Fig.8 we can see that the flow rate in the pump delivery system changes in real-time. It is not convenient to control dosing volume according to the average flow rate. So, in the initial experiments, the real-time integration method was used to calculate the dosing volume.

Using this method, the system begins to integrate the flow pulse when the piezoelectric pump began to work and turn off driven power of PZT pump in the exact moment when desired volume has been reached. For the real-time integration method, the driving voltage amplitude and frequency do not change at work, and there will be a residual volume adds to the overall dosing volume, as shown in Fig.9.

From Fig.9 we can see that the flow rate decrease gradually when turn off the driving voltage of PZT pump. Thus, a residual volume will be introduced. And the higher the driving voltage amplitude, the larger the residual volume is, as shown in Table 1. So in order to solve this problem, an effective method is to reduce the driving voltage amplitude before turn off the driving voltage of the PZT pump.

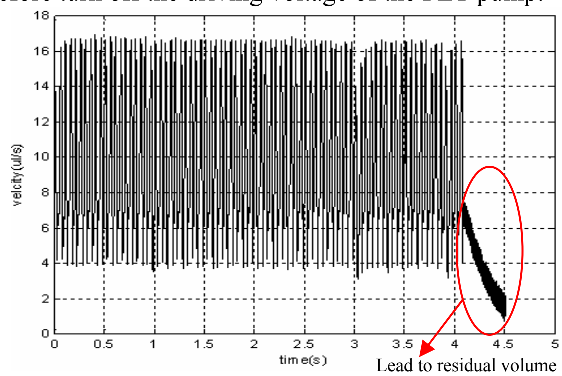


Fig. 9 The velocity profile during dispensing process (pump driving voltage amplitude is 58V and frequency is 20Hz).

Table 1 The dosing conditions under different driving voltage, and the voltage frequency is 20Hz, desired volume is 40μL

Driving amplitude (V)	*Dosing Volume (μL)*	*residual Volume (μL)*	*the whole dosing time (s)*	*residual dosing time (s)*
16	39.9908	1.3030e-004	112.0501	7.571 x10^{-5}
23	39.9912	1.3056e-004	70.8791	7.683x10^{-5}
30	40.1256	0.1353	48.3963	0.0013
37	40.7611	0.7698	27.6676	0.7506
44	41.4861	1.4944	15.7375	1.0495
51	42.0252	2.0322	11.5869	1.2769
58	42.7258	2.7355	9.8745	1.4475
65	43.4269	3.4368	7.8476	1.6026
70	43.9626	3.9718	7.2389	1.6649

First, the PID control strategy is proposed to adjust the driving voltage amplitude. And the normally PID method can be expressed in (1).

$$u(k) = K_p e(k) + K_i \sum_{j=0}^{k} e(j) + K_d [e(k) - e(k-1)] \quad (1)$$

u(k) is the output driving voltage ; *e(k)* is dosing volume error ; and K_p , K_i and K_d are the PID parameters.

From the formulae (1) we can see that the driving voltage will reduce as the dosing volume error decrease gradually. So using the PID control method could reduce the residual volume and dosing precisely. Look at Table 2, it shows the dosing conditions under different desired volume when use the PID control method. And the values of the PID controller is : K_p is set as the quotient obtained by dividing maximum pump driving voltage by desired dosing volume; K_i and K_d are set as zeros. During the dosing process, when the *e(k)* is small than 0.01μL, the system believe that it is the end of the control process and turn off the driving voltage of the PZT pump. From Table 2 we can see that the residual volume is reduced and the system could dose volume precisely.

While, in some applications, the whole dosing time is need to be as short as possible. The gain K_p is the key parameter that affect the settling time. If the K_p is chosen low enough, the residual will be small to ensure dosing precision, yet it will spends more time to dosing desired volume; oppositely, If the K_p is chosen relatively higher, the system could spend less to dosing desired volume, while the residual volume may be too large to ensure dosing precision.

Table 2 The dosing conditions under different desired volume, and the voltage frequency is 20Hz

Desired volume (μL)	*Dosing volume (μL)*	*Residual volume (μL)*	*The whole dosing time (s)*	*Residual volume dosing time (s)*
40	39.9907	3.1981e-004	12.8413	2.5394e-004
50	49.9913	2.1730e-004	17.1402	1.6790e-004
100	99.9907	3.0518e-004	38.5423	2.6344e-004
130	129.9911	2.8283e-004	46.3753	2.5143e-004
150	149.9904	2.6060e-004	57.2122	1.7432e-004
180	179.9903	1.1561e-004	65.9281	8.5486e-005
200	199.9907	2.9173e-004	70.4623	2.5003e-004
230	229.9903	2.0382e-004	80.5721	1.3521e-004
250	249.9912	3.8719e-004	91.8073	2.6735e-004

Thus, a fuzzy PID control strategy is proposed to adjust K_p. The schematic control block diagram is shown in Fig.10.

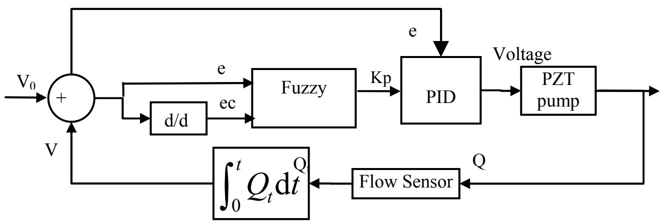


Fig.10 The schematicstructure of dosing volume control system

The input variables of the fuzzy controller are volume error (e) and volume error change rate (ec), and the output variable is the change of PID parameter-Proportion coefficient (K_p). Then, the PID controller calculates the driving voltage of PZT pump according to the Proportion coefficient (Kp) and the volume error (e). For the Fuzzy PID control method, the driving voltage amplitude can be modulated in real-time at work. When the dosing volume close to the desired volume, the driving voltage could be cut down to reduce the residual volume. Thus, dosing volume can be controlled precisely.

Table 2 The dosing conditions under different desired volume with fuzzy PID control method, and the voltage frequency is 20Hz

Desired volume (μL)	*Dosing volume (μL)*	*Residual volume (μL)*	*The whole dosing time (s)*	*Residual volume dosing time (s)*
40	39.9910	8.4924e-005	9.3691	8.5765e-005
50	49.9920	0.0010	10.1666	5.8862e-004
100	99.9919	0.0012	11.4438	8.3251e-004
130	129.9904	1.3237e-004	15.8511	8.8559e-005
150	149.9907	1.5990e-004	16.5962	1.6762e-004
180	179.9908	1.2324e-004	19.2411	8.7441e-005
200	199.9911	3.2279e-004	20.6623	2.5255e-004
230	229.9914	3.3803e-004	22.9713	2.5674e-004
250	249.9911	1.7918e-004	23.3701	1.3158e-004

Look at Table3, it shows the dosing conditions under under different desired volume when use the fuzzy PID control method. From Table 3 we can see that the whole dosing time reduces observably.

Finally, Comparison dispensing was carried out with different control methods. First, the pump based drug delivery system works with open-loop control method. The driving voltage of PZT pump is set according to calibration results. When the desired dosing volume is 100μL, the pump driving voltage is set as 58V and work 246 cycles to dispensing desired volume. The dosing time is 13s approximately. This experiment was carried out by 30 times, and the actual measured dosing volumes by flow sensor are drawn in Fig.11.

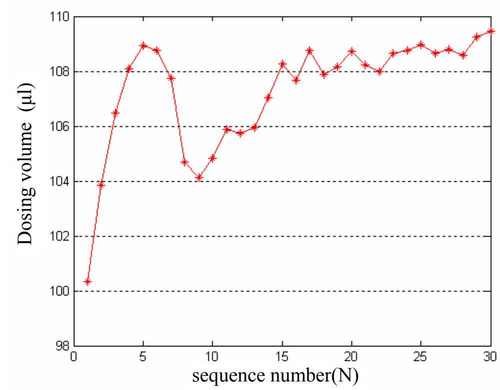


Fig. 11 Dispensed volume for open-loop when the desired volume is 100μL

From the results we can see that the volume error is about 10ul, and the dosing volume was higher than 100 μL because of the residual volume. Then, the system works with real-time integration closed-loop control method. During the experiments, the desired dosing volume is 100μL, and the dosing time is 39s approximately. The experiments were carried out by 30 times too. The actual measured dosing volumes by flow sensor are drawn in Fig.12.

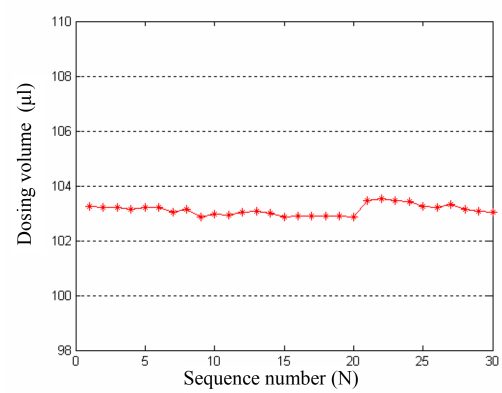


Fig. 12 Dispensed volume for real-time integration closed-loop when the desired volume is 100μL

From the results we can see that the actual measured dosing volume is slightly larger than the desired volume, and the volume error is less than 4μL.

Finally, experiments with fuzzy PID closed-loop control method were carried out. The desired dosing volume is 100μL, and the dosing time is 12s approximately. The experiments were carried out by 30 times. The actual measured dosing volumes by flow sensor are drawn in Fig.13. This picture shows that the dispensing precision enhanced when using PID control method and the dosing volume error is below 0.01μL.

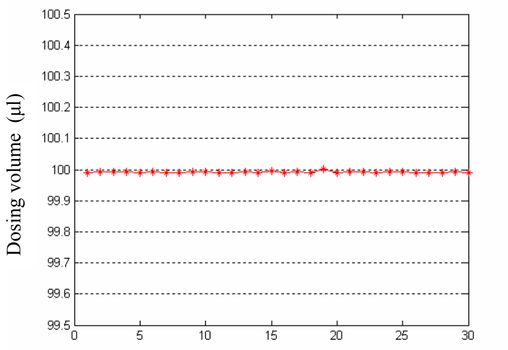


Fig.13. Dispensed volume for fuzzy PID closed-loop when the desired volume is 100μL

IV. CONCLUSIONS

An automated PZT pump-based precise liquid dosing system with feedback intelligent control strategy was presented in this paper. First, MEMS flow sensor based on measurement of pressure difference across a flow channel is developed to measure the real-time velocity of the pump dosing system. Then, in order to precisely control dosing volume of the PZT pump, a fuzzy PID control strategy is proposed. When using the Fuzzy PID control method, the driving voltage amplitude of the PZT pump can be modulated in real-time to precisely dispensing desired drug volume without pre-calibration. Finally, dispensing experiment was carried out to show that the drug dosing system could precisely delivery volume with error smaller than 0.01μL when desired volume is 100μL.

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REFERENCES

[1] W.J. Spencer, W.T. Corbett, L.R. Dominguez, et al., "An electronically controlled piezoelectric insulin pump and valves", IEEE Trans. Sonics Ultrasonbics, SU-25 3, pp.153–156, 1978
[2] P. Woias, "Micropumps—summarizing the first two decades", Microfluidics and BioMEMS 4560 pp.39–52, 2001
[3] O.C. Jeong, S.S. Yang, "Fabrication and test of a thermopneumatic micropump with a corrugated p+ diaphragm,"Sensors and Actuators, A: Physical,Vol. 83, pp.249–255,May 22, 2000
[4] T. Bourouina, A. Bosseboeuf, J.-P. Grandchamp, "Design and simulation of an electrostatic micropump for drug-delivery application," J. Micromech. Microeng. Vol.7 pp.186–188, 1997
[5] Sebastian B¨ohm, Bj ¨ orn Timmer, Wouter Olthuis et al.. "A closed-loop controlled electrochemically actuated micro-dosing system." J. Micromech. Microeng. Vol.10, pp. 498–504, May2000
[6] E. Makino, T. Mitsuya, T. Shibata, "Fabrication of TiNi shape memory micropump," Proceedings of SPIE - The International Society for Optical Engineering, v 3891, p 328-335, 1999
[7] Guo, Shuxiang, Sun, Xuesong, Ishii, Kouhei et al.. "SMA actuator-based novel type of peristaltic micropump." Proceedings of the 2008 IEEE International Conference on Information and Automation, ICIA 2008, p 1620-1625, 2008,
[8] Paolo Dario, Maria Chiara Carrozza, Benedetto Allotta, Eugenio Guglielmelli. "Micromechatronics in Medicine." IEEE/ASME transactions on mechatronics,Vol.1(2), pp.137-148, Jun 1996
[9] A. Hatch, A.E. Kamholz, G. Holman, et al., "A ferrofluidic magnetic micropump, "J. Microelectromech. Syst. Vol.10,pp. 215–221,2001
[10]Min Hu, Hejun Du, Shihfu Ling. "A Digital Miniature Pump for Medical Applications." IEEE/ASME Transactions on mechatronics, Vol.7(4) , pp.519-523, Dec 2002
[11]L. Cao, S. Mantell, D. Polla, "Design and simulation of an implantable medical drug delivery system using microelectrome chanical systems technology," Sensors and Actuators, A: Physical,Vol.94,pp.117–125,2001
[12] J. Cunneen, Y.-C. Lin, S. Caraffini, et al., "A positive displacement micropump for microdialysis," Mechatronics, Vol.8 pp.561–583,1998
[13]Chou-Lin Wu, Jinn-Cherng Yang, Ying-Chi Chen. Low Power Consumption PZT Actuated Micro-Pump. 2006 International Microsystems, Packaging, Assembly Conference Taiwan. pp. 65-68, 2006
[14] C.G.J. Schabmueller, M. Koch, M.E. Mokhtari, et al., "Self-aligning gas/liquid micropump," J. Micromech. Microeng. Vol.12 , pp. 420–424, 2002
[15] Doll, A. , Goldschmidtboeing, M., Heinrichs et al. A piezoelectric bidirectional micropump for a medical application. *American Society of Mechanical Engineers, Fluids Engineering Division (Publication) FED*, v 260, p 151-159, 2004,
[16] K. Junwu, Y. Zhigang, T. Kehong, et al., "Pumping performance of a new piezoelectric pump for drug delivery," J. Biomed. Eng. Vol. 21 (2) pp.297–301,2004
[17]Bashash, S., Jalili, N..Robust "Adaptive Control of Coupled Parallel Piezo-Flexural Nanopositioning Stages".IEEE/ASME Transactions on mechatronics.Vol.14(1),pp.1-20, Feb 2009
[18]Bhikkaji, B, Moheimani, S.O."Integral Resonant Control of a Piezoelectric Tube Actuator for Fast Nanoscale Positioning." IEEE/ASME Transactions on mechatronics.vol.13(5), pp. 530-537, Oct 2008
[19]Ye, Fang, Li, Yi-Li, Zhang, Jian-Hui. Dynamic research on actuator for valveless piezoelectric pump with Y-shape tubes. Guangxue Jingmi Gongcheng, Vol16, n 12, pp. 2358-2365, December 2008
[20] E. Stemme, G. Stemme, "A valve-less diffuser/nozzle based fluid pump, " Sensors and Actuators A, Vol. 39, pp. 159-167,1993
[21]Sun, Xiao-Feng , Li, Xin-Xin, Yang, Zhi-Gang et al. Piezoelectric membrane pump with series-connected double chambers and holistic opening valve. Journal of Jilin University (Engineering and Technology Edition), Vol 36, n 4, pp. 529-533, July 2006
[22]Lee, Dong Gun , Or, Siu Wing, Carman, Gregory P. Design of a piezoelectric-hydraulic pump with active valves. Journal of Intelligent Material Systems and Structures, Vol15, n 2, pp. 107-116, February 2004
[23]D. Maillefer, Harald van Lintel, G.-R. Mermet, R. Hirschi, SA Debiotech, "A high-performance silicon micropump for an implantable drug delivery system," MEMS 99, Orlando, USA, pp. 541-546.
[24] T.S.J. Lammerink, M. Elwenspoek, J.H.J. Fluitman, "Integrated micro-liquid dosing system," MEMS 93, Fort Lauderdale, USA, pp. 254-259.
[25] V. Gass, B.H. van der Schoot, S. Jeanneret, N.F. de Rooij, "Integrated flow-regulated silicon micropump, "Sensors and Actuators A, Vol. 43 , pp.335-338, 1994
[26]Nicolas Szita, Ruben Sutter, JuÈrg Dual, Rudolf A. Buser, "A micropipettor with integrated sensors," Sensors and Actuator A, Vol. 89, pp. 112-118, 2001
[27]Kamlesh D. Patel, Michael S. Bartsch, Matthew H. McCrink, etal. "Electro kinetic pumping of liquid propellants for small satellite microthruster applications." Sensors and Actuators.Vol. 132, pp.461-470, June 2008