MEMS Based Energy Harvesting Controler Using Fuzzy Logic

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Abstract—This paper presents the design and simulation of MEMS based energy harvester controller. Energy harvesting from physical motion such as finger motion, heart beating, walking and running are becoming so important now-a-days. In this study outputs voltage and current of the MEMS based energy harvester can be controlled by using fuzzy logic based control system. A new way of controlling the outputs by changing the inputs has been proposed in this study. The system has been developed in MATLAB using fuzzy logic Mamdani model.Two inputs pressure and area have been selected. The three membership functions to the input parameters have been assigned. The two outputs like voltage and current are selected for output power. Three membership functions are also assigned to the outputs. The system works according to the rules defined in the fuzzy inference system (FIS). The results according to suggested rules belonging to assigned MFs have been displayed in surface viewer.Different rules of combinations were defined in MATLAB rule editor and we used AND logic for simulation. The rsults obtained from fuzzy logic controller have been verified by using Mamdani's formula for specific values of the inputs and the outputs. As there is only 1% error for both the outputs, current and voltage, this shows that the system performs very well.

Index Terms — Fuzzy logic, Fuzzy rule editor, Fuzzy Inference system, MEMS, Membership functions, MATLAB.

I   Introduction

Vibrations are one of the most common phenomena that exist at all the time and at everywhere and in every field of life.Some common and simple natural acts occurring in nature that can produce vibrations are figure motion ,heart beating, walking, running and any mechanical instrument in action. The mechanical actions like running cars or any other function of the human body is the best source to produce vibrations which can easily be converted into electrical energy through MEMS based energy harvesters. This ambient energy would be useful for wearable devices, household applications, sensors for medical implants, compute or communicate practically everywhere.Very low power 10-100μW is requied for the normal operation of VLSI design and lithium-ion batteries can produce a power 160W.h/kg but it is very large in size and has a limited life [1]. The MEMS based energy harvesting devices approch in different fields eliminating the need for wiring, chemical batteries or power sources which are bulkier and higher in cost. Therefore, MEMS based energy harvester becomes more appealing or even essential. MEMS based energy harvesters are so good that we can produce a power of 1μW only by using a device of dimensions 1cm×1cm and this power can easily be converted into 1mW if it is given to a little capacitor. [2]. Lin et al. proposed an intelligent fuzzy logic system whose basis was artificial neural network. It was seen that by linking the self-organized and supervised system the results taken were astonishing. The system considered was user friendly and could be easily understood by anyone. The system was seen to be benevolent, solid and provide the best results [3]. Castro presented a work on the topic how does fuzzy logic is an approximate method and why it has an edge over other logics. He also described why does fuzzy logic shows great performance while other logics cannot do so. People mostly criticize the performance of fuzzy controller but in his work he proved that the fuzzy controller had great impact on daily life problems.Castro had shown both quantitative and qualitative approach to the fundamental problems[4].Tang et al. proposed a fuzzy logic based system for creating genetic algorithm. He used a method in which a system was divided into two different inputs. Fuzzy membership functions were used to define the parameters of inputs. Fuzzification was done on the input and rules were defined, then defuzzification was done on the outputs. Fuzzy logic based system was used due to its unique way of attempting complex and non-linear problems [5]. Sue et al. [6] (2011) particularly investigate and characterize the energy harvesters that can be used to produce power from human body. They also reviwed the currently available MEMS based energy harvester. They evaluate and briefly described power gain, different methods for tunning the frequency and showed that micro-energy harvesters are biologically harmless. Liu et al. [7] (2012) fabricated a new piezoelectric cantilever at microlevel for harvesting vibrational energy at very small frequencies and low accelerations. They obtained a maximum potential difference 42 mV and a power of $0.31 \, \mu W \, g^{-2}$ by acceleration of $0.06g$. Elizabet et al. [8] (2012) studied the enhancement of the mechanical response of MEMS based energy harvester by optical excitation. In this way they

gave a pathway for the moving structures to response with heating effect. They showed how a MEMS based connected structure can responds mechanically to the temperature change of the element. The heating purpose they used infrared radiations. Liu et al. [9] (2012) presented a piezoelectric energy harvester (PEH) system with a large operating bandwidth. They showed that their device could produce an output power of 34 to 100 nW. Dhakar et al. [10] (2014) presented a triboelectric energy harvesting devices. The maximum output power measured from the device was observed to be $0.69\,\mu$W. Jia et al. [11] (2014) reported a piezoelectric MEMS cantilever vibrational energy harvester. In this way they were able to produce 0.7μW with 7g and 2.56 µW at 3 ms^{-2}. Cao et al.[12] (2011) designed a piezoelectric cantilever. They used finite element method (FEM) for simulation. They verified their results and showed that the optimized cantilevered piezoelectric energy harvesters could produce a 56V peak open-circuit voltage. The proposed method would be suitable for optimization design of piezoelectric energy harvester. Bala et al. [13] (2014) described an electrode position optimization in magnetoelectric sensors based on piezoelectric bilayer cantilever substrates. They applied the Finite element method (FEM) for simulations.A 15% higher signal voltage across the piezoelectric layer was obtained for optimally positioned electrodes with a simple layered cantilever and an insulating magnetostrictive material. They also described that the signal voltage was increased 25% for a trenched cantilever. Kellogg et al.[14] (2011) studied piezoelectric energy harvester. They said that by increasing the length of the cantilever the stress level of the cantilever increased and in this way power output of each piezoelectric element increased. Leadenham et al. (2014) [15] described a piezoelectric cantilever for sensing, actuation and energy harvesting. They found the the proposed model and experimental investigation were in close agreement with each other. Mutlaif et al.[16] (2015) presented a mathematical derivations for piezoelectric energy harvester.They used MATLAB and COMSOL Multiphysics software for Simulation.They also studied the the effect of length and shape of the cantilever beam on the output voltage. Rivadeneyra et al. [17] (2015) reported a low frequency <300 Hz vibrational energy harvester due to the fact that many industrial and commercial devices operate at these frequencies. In their paper they investigate the influence of perforating sections of the Si beam had on the resonant frequencies of the cantilever by numerical simulation. Kim et al.[18] (2013) fabricated dual-beam cantilevers on the microelectromechanical system (MEMS) scale with an integrated Si proof mass. They used the finite element method (FEM) with parametric analysis carried out in the design process. According to simulations, the resonant frequency, voltage, and average power of a dual-beam cantilever was 69.1 Hz, 113.9 mV, and 0.303µW, respectively, at optimal resistance and 0.5 g. The harvested power density of the dual-beam cantilever compared favorably with the simulation. Their experimental results for the resonant frequency, voltage, and average power

density were 78.7 Hz, 118.5mV, and 0.34 µW. The error between the measured and simulated results was about 10%. The maximum average power and power density of the fabricated dual-beam cantilever at 1 g were 0.803µW and 1322.80 µW cm^{-3}, respectively.

Fuzzy logic is basically a flexible technique and is a numerical representation of system in which answer is just not only high or low, 0 or 1, ON or OFF and True or False. It is a free technique which is not bounded by any specific states. For example in thermally heated metal where value is not just only hot or cold but also between them, this system could be easily developed by using fuzzy logic as it can tell that some part of the metal is at normal temperature. The most common way of using fuzzy logic is to solve it through MATLAB software. In this paper we have done the simulation for an efficient MEMS based energy harvester that can convert mechanical energy into electricity. The rsults obtained from fuzzy logic controller have been verified by using Mamdani's formula for specific values of the inputs and the outputs. As there is only 1% error for both the outputs current and voltage, this shows that the system performs very well.On the analysis of the results obtained from simulation we will draw the conclusion.

II   DESIGN METHODOLOGY

A   Designing in MATLAB

FLC is comprises of two inputs with three membership functions and two outputs also with three membership functions. Fig. 1 shows two input variables: Pressure, Area and Voltage and Current as outputs.
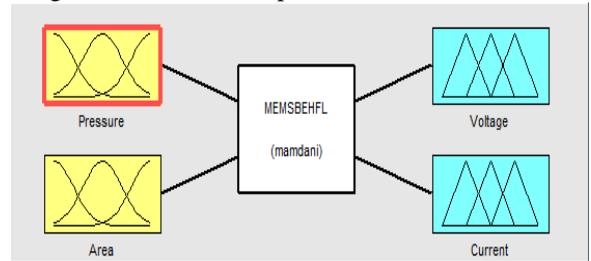
Figure 1 Fuzzy Logic Controller (FLC)

FLC system in Fuzzy Logic Inferring System (FIS) editor could be assigned by several numbers of inputs but here it has two inputs and each input has three membership functions (MFs). The ranges should be selected according to the desired values of input (MFs) and output (MFs). The ranges of inputs and output have been taken (0-100) for both inputs and outputs as shown in table1

Table 1 Ranges selected for inputs and outputs

MFs	Ranges	Pressure	Area	Voltage	Current
MF$_1$	0-50%	Low (L)	Very Small (V)	Low (L)	Low (L)
MF$_2$	0-100%	Medium (M)	Small(S)	Medium(M)	Medium (M)
MF$_3$	50-100%	High (H)	Large(L)	High(H)	High(H)

The figure 2 shows that how the common regions have been differentiated. The first overlapped region of the range 0 to 50 and 0 to 100 is called Region 1 and second overlapped region of range 0 to 100 and 50 to 100 is called Region 2. It is same for the inputs and the outputs. The calculations have been taken according to this regional division
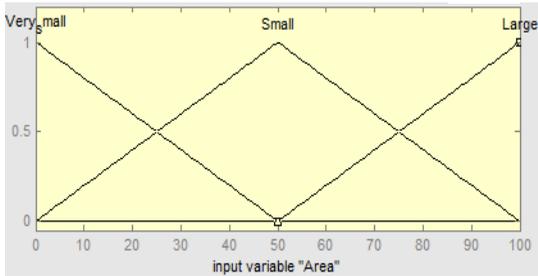
Figure 2 Division of the regions

In designing of this system different rules have been established for the better result. The rules involve the simple If and Then statement and the AND logic.

Table 2 Rules for the inputs and output

IF		THEN	
Pressure	Area	Voltage	Current
L	V	L	L
L	S	M	M
L	La	M	M
M	V	M	M
M	S	M	M
M	La	M	M
H	V	H	H
H	S	M	M

Fig.3, Fig.4, show membership functions of input variables and Fig.5 and Fig.6 show the membership functions of the output variables Voltage and Current.
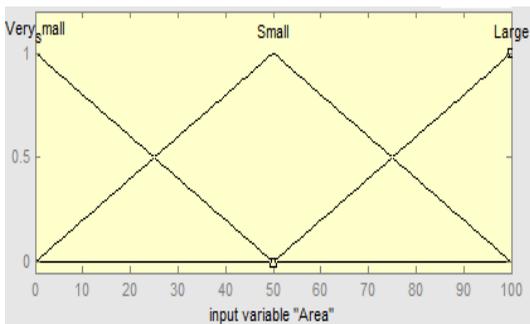
Figure 3 MFs graph for Area
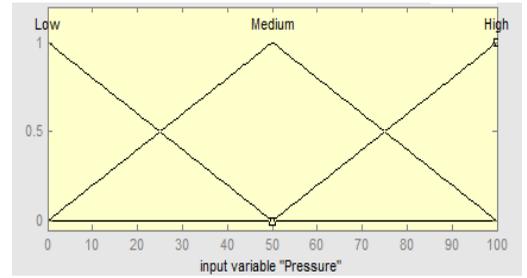
Figure 4 MFs graph for pressure
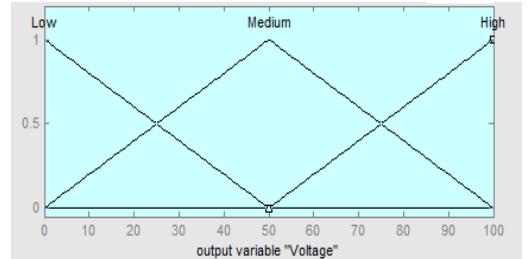
Figure 5 MFs graph for the output voltage
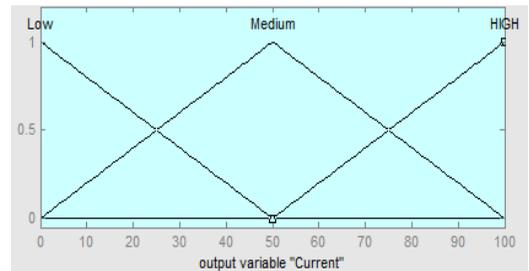
Figure 6 MFs graph for the output current
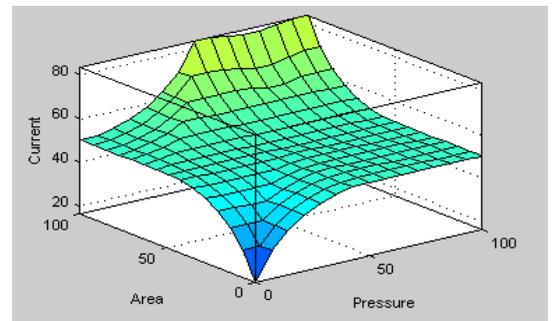
Figure 7 surface viewer graph among area, presure and output voltage

This graph shows that by increasing the pressure output voltage will increase but for medium to high value of the pressure the output voltage will be high. Similarly by increasing the area the output voltage will increase but for the large value of the area the output voltage will remain medium.
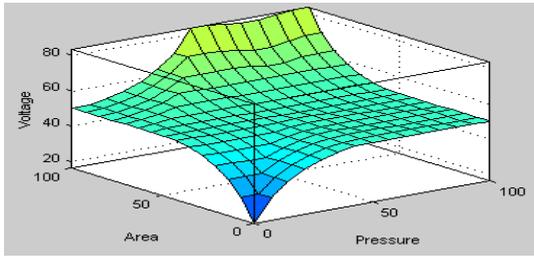
Figure 8 Surface viewer graphs among area, presure and output current

This graph shows that by increasing the pressure the output current wil lincrease but for the medium and high value of the pressure the current wiil remain high. Similarly, by increasing area the value of the output current increases but for the large value of area the output current will remain medium.

B- Algorithm design for Flow Controller System

For design algorithm of fuzzy logic controller the %age value of the input and output parameters are as

Pressure = 23.5
Area = 75.3
Voltage = 55.6
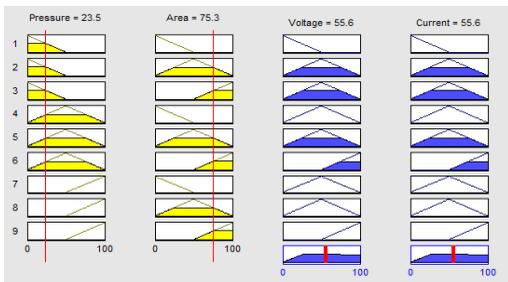
Figure 9 graphs showing the % age values of the input parameters pressure and area and the corresponding MATLAB SIMULATED values of the output voltage and current

The value of the Pressure (23.5) lies in region 1as shown in the fig. 10. Membership functions for region 1 are Low (L) and Medium (M). The MFs mf_1 and mf_2 for these values are mf_1 = 50-23.5/50 =0.53 and mf_2 = 1 - mf_1 = 1-0.53 =0.47
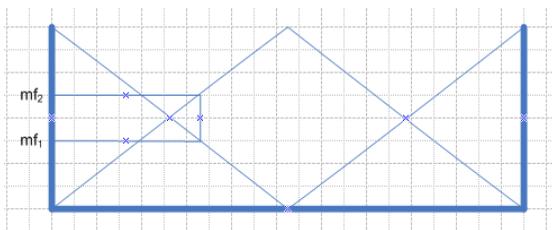
Figure 10 Graph showing the values of the membership functions mf_1 and mf_2 for the Pressure.

For Area (75.3) values lies in the region 2 as shown in the fig. 11. Membership functions for region 2 are Very Small (V) and Small (S). The MFs mf_3 and mf_4 for these values are

mf_3 = 100 − 75.3/50 = 0.494
mf_4 = 1 − mf_3 =1- 0.494= 0.506
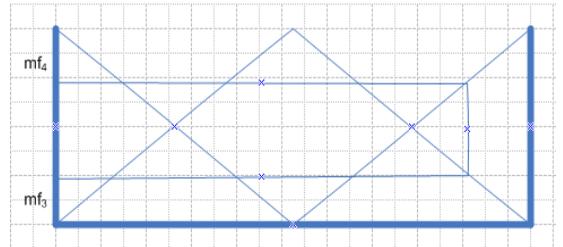
Figure.11 Graph showing the values of the membership functions mf_3 and mf_4 for the Area

For Voltage (55.6) value lies in region 2 as shown in fig. 12. Membership functions for region 1 are Low(L) and Medium(M). The MFs mf_5 and mf_6 for these values are

mf_5 = 100 − 55.6/50 = 0.888
mf_6 = 1 - mf_5 = 1- 0.888 = 0.112
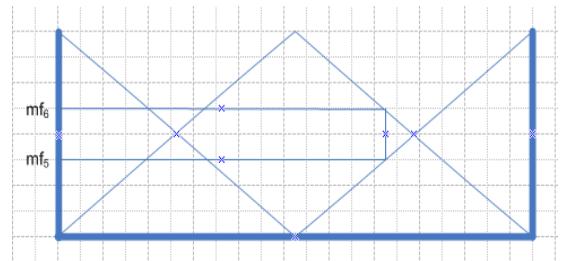
Figure 12 graph showing the values of the membership functions mf_5 and mf_6 for the Voltage

Selected rules for fuzzy logic controller according to value of input parameters (Pressure =23.5, Area =75.3) are listed in Table 3.

Table 3 Used for Selected Rules

Rules	Pressure	Area	Voltage
R_1	L	S	M
R_2	L	La	M
R_3	M	S	M
R_4	M	La	H

The value of pressure is lying in Region 1 P= 23.7; Area is in Region 2 A= 75.3, Voltage is in region 2 V = 55.6 and current is in region 2 I=55.6. Pressure the 1st input of the system; whose value lays in Region 1 in MF graphs. Mfs are Low (L) and High (H).The mfs mf_1 and mf_2 for these values

are $mf_1 = 0.53$ and $mf_2 = 0.47$.

The 2nd input parameter for the system is Area; whose value lays in Region 2 of MF graphs. Mfs are: Small (S) and Large (L). The mfs mf_3 and mf_4 for these values are $mf_3 = 0.494$ and $mf_4 = 0.506$. The fisrt output parameter is Voltage whose value lies in region 2 of MF graphs.Mfs are Medium (M) and High (H).The mfs mf_5 and mf_6 for these values are $mf_5 = 0.888$ and $mf_6 = 0.112$.Table 4 shows the singleton values for this system:

Table 4 shows the singleton values

Rules	Pres-sure	Area	Voltage	Singleton Value
R_1	L	S	M	0.5
R_2	L	La	M	0.5
R_3	M	S	M	0.5
R_4	M	La	H	1

Table 5 shows the rules corresponding to the mfs

Rules	Membership Functions
R_1	$mf_1 \wedge mf_3 \wedge mf_5 = 0.53 \wedge 0.494 \wedge 0.888 = 0.494$
R_2	$mf_1 \wedge mf_3 \wedge mf_6 = 0.53 \wedge 0.494 \wedge 0.112 = 0.112$
R_3	$mf_1 \wedge mf_4 \wedge mf_5 = 0.53 \wedge 0.506 \wedge 0.888 = 0.506$
R_4	$mf_1 \wedge mf_4 \wedge mf_6 = 0.53 \wedge 0.506 \wedge 0.112 = 0.112$

Calculations using the Mamdani's Formula

By using the formula for Mamdani'model output is calculated for both the conditions as
The value of pressure is lying in Region P= 23.7; Area is in Region 2 A= 75.3, Voltage is in region 2 V = 55.6 and current is in region 2. Pressure the 1st input of the system; whose value lays in Region 1 in MF graphs. Mfs are Low (L) and High (H).The mfs mf_1 and mf_2 for these values are $mf_1 = 0.53$ and $mf_2 = 0.47$.

The 2nd input parameter for the system is Area; whose value lays in Region 2 of MF graphs. Mfs are: Small (S) and Large (L). The mfs mf_3 and mf_4 for these values are $mf_3 = 0.494$ and $mf_4 = 0.506$.
Where Ri are rules of table 5 and Si are singleton values of table 3.Here singleton values corresponds to 2 different variables of current 0.5 for Medium and 1 for high.
Hence $\Sigma S_i \times R_i = S_1 \times R_1 + S_2 \times R_2 + S_3 \times R_3 + S_4 \times R_4$
$= 0.50 \times 0.494 + 0.5 \times 0.112 + 0.5 \times 0.506 + 1 \times 0.112 = 0.247 + 0.056 + 0.253 + 0.112 = 0-668$

$\Sigma Ri = R_1 + R_2 + R_3 + R_4 = 0.494 + 0.112 + 0.506 + 0.112 = 1.224$
Flow controller = [$\Sigma Ri \times Si / \Sigma Ri$] = 0.668/ 1.224 = 0.546

MATLAB SIMULATION VALUE= 0.556
CALCULATED VALUE= 0.546

Difference= 0.556-0.546 = 0.010

Percentage error will be only 1% which is very small; therefore, the proposed system will performed well.
The value of pressure is lying in Region P= 23.7; Area is in Region 2 A= 75.3, Voltage is in region 2 V = 55.6 and current is in region 2. Pressure the 1st input of the system; whose value lays in Region 1 in MF graphs. Mfs are Low (L) and High (H).The mfs mf1 and mf_2 for these values are $mf_1 = 0.53$ and $mf_2 = 0.47$.The 2nd input parameter for the system is Area; whose value lays in Region 2 of MF graphs. Mfs are: Small (S) and Large (L). The mfs mf_3 and mf_4 for these values are $mf_3 = 0.494$ and $mf_4 = 0.506$. The second output parameter is Current whose value lies in region 2 of MF graphs.Mfs are Medium (M) and High (H).The mfs mf_5 and mf_6 for these values are
$$mf_5 = 100 - 55.6/50 = 0.888$$
$$mf_6 = 1 - mf_5 = 1 - 0.888 = 0.112$$

Hence
$\Sigma S_i \times R_i = S_1 \times R_1 + S_2 \times R_2 + S_3 \times R_3 + S_4 \times R_4$
$= 0.50 \times 0.494 + 0.5 \times 0.112 + 0.5 \times 0.506 + 1 \times 0.112 = 0.247 + 0.056 + 0.253 + 0.112 = 0.668$

$\Sigma R_i = R_a + R_b + R_c + R_d = 0.494 + 0.112 + 0.506 + 0.112 = 1.224$
Flow controller = [$\Sigma Ri \times Si / \Sigma Ri$] = 0.668/ 1.224 = 0.546

MATLAB SIMULATION VALUE= 0.556
CALCULATED VALUE= 0.546

Difference= 0.556-0.546 = 0.010

Percentage error will be only 1% which is very small; therefore, the proposed system will perform well.

III   RESULTS AND DISCUSSIONS

Fuzzy logic (FL) based control MEMS energy harvester is being proposed here for the control of outputs voltage and current of the MEMS based energy harveste. The given system contains FL controller which has two inputs (pressure and area) and 2 outputs (voltage and current).AND logic and the Mamdani's model has been used here the results of whom are given below:
MATLAB SIMULATION VALUE= 0.556
CALCULATED VALUE= 0.546
Difference= 0.556-0.546 = 0.010

Percentage error will be only 1% for both the out puts Voltage and current, which is very small; therefore, the proposed system will performed well.

IV   Conclusion

In this study outputs voltage and current of the MEMS based energy harvester can be controlled by using fuzzy logic based control system. A new way of controlling the outputs by changing the inputs has been proposed. The system has been developed in MATLAB using fuzzy logic Mamdani model.Two inputs pressure 75.5 and area 23.5 have been selected. The three membership functions to the input parameters have been assigned. The two outputs like voltage 55.6 and current 55.6 are selected for output power. Three membership functions are also assigned to the outputs. The system works according to the rules defined in the fuzzy inference system (FIS). The results have been displayed in surface viewer.Different rules of combinations were defined in MATLAB rule editor and we used AND logic for simulation. The rsults obtained from fuzzy logic controller have been verified by using Mamdani's formula for specific values of the inputs and the outputs. As there is only 1% error for both the outputs, current and voltage, this shows that the system performs very well.

Reference

[1] S.J.Roundy, "Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration to Electricity Conversion".PhD thesis University of California,Berkely (2003).

[2] Zhong Lin Wang, Youtube video on piezoelectricity….energy harvesting at the nanolevel.

[3] Chin-Teng Lin, C. S. George Lee, "Neural-Network-Based Fuzzy Logic Control and Decision System" IEEE Transactions on Computers, Vol. 40, No. 12, December 1991.

[4] J.L.Castro"Fuzzy Logic Controllers Are Universal Approximators"IEEE Transactions on Systems, Man, and Cybernetics, Vol 25, No. 4, April 1995.

[5] K.S.Tang, K.F.Man, Z.F.Liu, S.Kwong "Minimal Fuzzy Memberships and Rules Using Hierarchical Genetic Algorithms" IEEE Transactions On Industrial Electronics, Vol. 45, No. 1, February 1998.

[6] C.Y.Sue, N.Chyuan, "Human powered MEMS-based energy harvest devices". Science direct Applied Energy,Volume 93, pp 390–403(2012).

[7] H.Liu, C.Lee, T.Kobayashi, C.J.Tay And C.Quan, "Investigation Of A MEMS Piezoelectric Energy Harvester System With A Frequency-Widened-Bandwidth Mechanism Introduced By Mechanical".Microsystem Technologies (2012), Vol.18, Issue 4, pp497-506(2012).

[8] E.A.Dobisz, L.A.Eldada, "Study of two-dimensional device-error-redundant single-electron oscillator system". Nanoengineering: Fabrication, Properties, Optics, and Devices IX, Vol. 8463 (2012).

[9] H.Liu, C.Lee, T. Kobayashi, C. J. Tay and C. Quan, "A   new S-shaped MEMS PZT cantilever for energy harvesting from low frequency vibrations below 30 Hz".Smart Matrials and Structures Vol.21 No.3 (2012).

[10] L. Dhakar, F. E. H. Tay and C.Lee, "Investigation of contact electrification based broadband energy harvesting mechanism using elastic PDMS microstructures", Vol.24, No.10.(2014).

[11] Jia, Y. Seshia, A. A, "White Noise Responsiveness of an AlN Piezoelectric MEMS Cantilever Vibration Energy Harvester" Journal of Physics: Conference Series, Volume 557, Issue 1(2014).

[12] C.Junyi, Zhou, S, Ren, X. Cao, Binggang, "Piezoelectric cantilevers optimization for vibration energy harvesting".Third International Conference on Smart Materials and Nanotechnology in Engineering. Vol. 9,pp 8409 (2011).

[13] Bala, U.B.Krantz, C.Matthias, Gerken, Martina, "Electrode position optimization in magnetoelectric sensors based on magnetostrictive-piezoelectric bilayers oncantilever substrates". Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on Vol.61, Issue 3 (2014).

[14] Kellogg, A.Rick, A.Sumali and Hartono, "Piezoelectric energy harvester having planform-tapered interdigitated beams".United state patent Kellog et al, Patent No.: US 7,948,153 B1 (2011)

[15] Leadenham, Stephen,Erturk, Alper, "Global nonlinear electroelastic dynamics of a bi morph piezoelectric cantilever for energy harvesting, sensing, and actuation".Spie digital library Active and Passive Smart Structures and Integrated Systems (2014), Vol.9057, Issue 02, doi 10.1117/12.2045161,(2014).

[16] A.Muthalif, A.Gani, "Optimal piezoelectric beam shape for single and broadband vibration energy harvesting: Modeling, simulation and experimental results".Elsevier (2014).

[17]R.Almudena,S.Rueda,J.Manuel,O'Keeffe,Rosemary,B. Jesus,J.Nathan,M.Alan,L.V.J.Antonio,"Tunable MEMS Piezoelectric Energy Harvesting Devices" Microsystems Technologies (2015), DOI: 10.1007/s00542-015-2455-1.

[18]K.Moonkeun, L.S.Kyun, Y.Y.Suk, J. Jaehwa, M. Nam Ki, K.K.Ho, "Design and Fabrication of Vibration Based Energy Harvester Using Microelectromechanical System Piezoelectric Cantilever for Low Power Applications". Journal of Nanoscience and Nanotechnology, Vol. 13, No. 12, pp. 7932-7937 December (2013).