To my parents
ACKNOWLEDGEMENTS

First of all, I would like to thank and express my sincere gratitude to my research advisor Professor Yogesh B. Gianchandani for his support and encouragement throughout my doctoral study. This dissertation work would not have been possible without his support and mentoring. I would also like to thank my committee members Professor Kensall D. Wise, Professor Noel C. Perkins, Professor Katsuo Kurabayashi and Professor Jorge A. Marrero for their discussions and guidance.

I would also like to thank Dr. Tao Li and Dr. Naveen K. Gupta for being a great mentor to me and for training me on the µEDM and µUSM. I owe a lot to them for all the valuable suggestions and discussions they have provided me during my doctoral study. I would like to thank Dr. Hiro and Prof. Maharbiz for their help with insect stimulation work. I would also like to thank Dr. Christine Eun, Jeff, Trushal and Robert for their help with interface circuit design. I am also indebted to all the WIMS and SSEL staff especially to Trasa Bukhardt and Fran Doman for taking care of all my administrative work and research purchases.

I would like to thank my research group members, Bhaskar, Amar, Jong, Weibin, Tao, Naveen, Mark, Christine, Scott Wright, Scott Green, Allan, Heidi, Fatih, Erwin, Jun, Ravish, Seungdo and Xin Luo. It has been a wonderful learning experience working with them. I would also like to thank my friends, Razi, Erkan, Angelique, Sister Mary.
Elizabeth, Ning, Ali, Amir, Jae Yoong, Daniel, Niloufār, Jeff, James, Mahdi, Seow Yuen, Andrew Gross, Tzeno, Jay, Hanseup, Farah, Trushal, Anurag, Shantanu, Ashwini, Rahul, Ajith, Bharath, Hari Prasath and many others who have made my stay at University of Michigan a memorable one. I would also like to thank my undergraduate advisor Professor Krishnan Balasubramaniam for his support and encouragement to do my doctoral study.

Finally, I would like to thank my parents and family members for their unlimited love and encouragement. Without them I would have never reached this day.
TABLE OF CONTENTS

DEDICATION .................................................................................................................................................. ii

ACKNOWLEDGEMENTS ........................................................................................................................ iii

LIST OF FIGURES .................................................................................................................................... ix

LIST OF TABLES ...................................................................................................................................... xv

LIST OF APPENDICES ............................................................................................................................ xvii

ABSTRACT ................................................................................................................................................ xvi

Chapter

1. INTRODUCTION ..................................................................................................................................... 1

1.1 Role of microheaters in microsystems .......................................................................................... 2

1.2 Ultrasonic heat generation ............................................................................................................ 3

1.3 Ultrasound generation methods .................................................................................................. 4

1.3.1 Laser ultrasonics ...................................................................................................................... 4

1.3.2 Electromagnetic acoustic transducers .................................................................................. 5

1.3.3 Piezoelectric transducers ......................................................................................................... 6

1.3.4 Micromachined ultrasonic transducers (MUTs) ............................................................... 7

1.4 Heat generation in PZT devices ..................................................................................................... 9

1.5 Applications ...................................................................................................................................... 11

1.5.1 Needle tract cauterization during needle aspiration biopsy .............................................. 11

1.5.1.1 Existing tissue cauterization methods ........................................................................ 13

1.5.1.2 Past work on ablation for biopsy procedure ............................................................... 14

1.5.2 Microthermal stimulators for locomotion control of insects ............................................. 17

1.6 Research challenges addressed in this work ............................................................................. 20

1.7 Outline ............................................................................................................................................. 21
2. SIMULATION MODEL AND EXPERIMENTAL CHARACTERIZATION OF PIEZOCERAMIC HEATERS.................23
   2.1 Simulation model for temperature rise in PZT heater .........................24
       2.1.1 Theory.................................................................24
       2.1.2 Simulation model ..................................................28
   2.2 Device design and fabrication ................................................29
   2.3 Device and operating parameter characterization .......................32
       2.3.1 Experimental setup ................................................32
       2.3.2 Simulation model validation .....................................32
       2.3.3 Operating frequency selection ..................................34
       2.3.4 Effect of voltage offset and substrate material ...............37
       2.3.5 Stacked structure design .........................................38
       2.3.6 Biological tissue cauterization experiments ...................40
   2.4 Conclusions ........................................................................41

3. LOCOMOTION CONTROL OF AIRBORNE, AMBULATORY AND AQUATIC INSECTS USING MICROThermal STIMULATION .........42
   3.1 Design and fabrication ........................................................42
   3.2 Experimental results ..........................................................46
       3.2.1 Characterization of piezothermal stimulators ....................46
       3.2.2 Control of insect locomotion ......................................46
           3.2.2.1 Experiments on green June beetle .......................47
           3.2.2.2 Experiments on Madagascar hissing roaches ..........49
           3.2.2.3 Experiments on green diving beetles .................52
   3.3 Discussion .........................................................................54
       3.3.1 Scaling of piezothermal stimulators ..............................54
       3.3.2 Battery .....................................................................55
   3.4 Conclusions .........................................................................56

4. BIOPSY NEEDLE TRACT CAUTERIZATION AND IN-SITU CAUTERIZATION MONITORING USING EMBEDDED PIEZOCERAMIC MICREOHTEARS..................................................58
   4.1 Simulation model .................................................................58
       4.1.1 Tissue ablation model ..................................................58
4.1.2 Model for estimating resonance frequency shift due to cauterization..................................................61
4.2 Device design and fabrication .................................................................65
4.3 Experimental results ...........................................................................68
  4.3.1 Tissue cauterization ........................................................................68
  4.3.2 Sensing of the tissue cauterization ...............................................71
4.4 Conclusions .........................................................................................73

5. THE ACTUATION AND SENSING INTERFACE CIRCUITS FOR BIOPSY NEEDLE TRACT CAUTERIZATION TOOL .........................74
  5.1 Existing readout circuits for resonance frequency measurement ......75
    5.1.1 Impulse excitation .........................................................................75
    5.1.2 Phase lock loop ...........................................................................75
    5.1.3 Oscillators ..................................................................................76
  5.2 Design of proposed interface circuits ..................................................77
    5.2.1 Sensing circuit for resonance frequency shift measurement ........77
    5.2.2 Actuation circuit ..........................................................................79
  5.3 Simulation results .................................................................................80
  5.4 PCB layout and fabrication .................................................................85
    5.4.1 Sensing circuit .............................................................................85
    5.4.2 Actuation circuit ..........................................................................87
  5.5 Experimental results ...........................................................................88
    5.5.1 Resonance frequency measurement circuit testing .................88
      5.5.1.1 Experimental setup .................................................................88
      5.5.1.2 Testing of VCO .................................................................88
      5.5.1.3 Testing of Butterworth low pass filter ..............................89
      5.5.1.4 Testing of peak detection circuit .....................................91
      5.5.1.5 Testing of adder, amplifier and subtractor .....................91
      5.5.1.6 Testing of the complete circuit ........................................92
    5.5.2 Actuation circuit testing .................................................................95
  5.6 Conclusions ..........................................................................................95

6. CONCLUSIONS AND FUTURE WORK .....................................................97
  6.1 Conclusions ..........................................................................................97
6.2 Future work.................................................................................................................101

APPENDICES ..................................................................................................................104

BIBLIOGRAPHY ..............................................................................................................125

viii
LIST OF FIGURES

Figure 1.1: Schematic of an elementary EMAT .................................................................5

Figure 1.2: Response of a piezoelectric disk to an alternating voltage. (a) Piezoelectric crystal, (b) axis definition and (c) X cut vibrations are longitudinal and (d) Y- cut vibrations are transverse ..................................................................................6

Figure 1.3: Schematic of cross-section of (a) CMUT and (b) PMUT .................................8

Figure 1.4: Concept diagram of ultrasonic cauterization device for needle tract cauterization during biopsy procedure .......................................................................................12

Figure 1.5: (a) Comparison of the cost versus invasiveness of the existing thermal cauterization method with the present work. (b) Comparison of the procedure invasiveness with the ability for integrated tissue contrast sensing for various thermal ablation methods ...........................................................................................................16

Figure 1.6: (a) Concept of instrumented insect. (b) Enlarged side view of the head of the green june beetle with thermal stimulators near the antenna. (c) Photo of Madagascar hissing roach with implanted thermal stimulators ..........................................................19

Figure 2.1: Concept diagram of a PZT based cauterization tool ......................................23

Figure 2.2: Comparison of the simulated temperature rise of the PZT element for a given drive voltage bonded to a brass substrate. Different cross-sectional shapes were used, with same volume and cross-sectional area. The circular shape provides the most favorable response ........................................................................................................30

Figure 2.3: (a) Schematic of the device designed for simulation model validation. Schematic of the (b) unstacked PZT heater and (c) stacked PZT heater. (d) Photograph of the fabricated unstacked and stacked PZT heater ..............................................................31

Figure 2.4: Schematic of the test setup used in the characterization PZT heaters ............32

Figure 2.5: (a) Comparison of the simulated and experimental data for temperature attained for varying applied voltage by PZT elements bonded to a 3.3 mm thick brass plate. The properties of the material used in the simulation are provided in Table 2. (b) Comparison of the simulated and experimental temperature rise generated by the PZT
heater for varying input power when attached to elytra of a beetle carcass. The simulations were performed with fitted ultrasound attenuation coefficients of 1100, 170, 100, 1000 dB/m/MHz for the non-conductive epoxy, conductive epoxy, brass substrate and elytra, respectively. The measured thermal efficiency of the heater was 0.93˚C/mW at 85˚C.

**Figure 2.6:** (a) Thermal efficiency and electromechanical impedance of unstacked PZT heater bonded to a brass substrate as a function of frequency. (b) Thermal efficiency and coupling factor for various mode shapes observed in unstacked PZT heater bonded to brass.

**Figure 2.7:** (a) Comparison of temperature attained by PZT and conductance as a function of frequency of excitation for mode 2 on brass. (b) Comparison of thermal efficiency and electromechanical impedance of the PZT heater as a function of frequency for mode 2 on brass.

**Figure 2.8:** (a) Variation of normalized thermal efficiency (efficiency/offset /efficiencyzero-offset) with increase in the DC offset in the excitation voltage. The thermal efficiency was found to decrease with increase in the offset voltage. (b) Thermal efficiency of PZT microheater on different substrates. The efficiency of the heater was higher for highly damping substrates like tissues.

**Figure 2.9:** Normalized maximum temperature (Tmax/Tmax-unstacked) and efficiency (eff/effunstacked) attained by stacked PZT heater. The stacked heaters were tested in four modes of operation: actuation of lower element alone, actuation of upper element alone, symmetric actuation of both elements with electric field in same direction and anti-symmetric actuation of both elements with electric field in opposite direction.

**Figure 2.10:** Photograph of the cauterization of porcine tissue using unstacked PZT heater probe. The heater probe brands the tissue in 2-3 seconds with 10 VRMS. The interface temperature is ≈150˚C.

**Figure 3.1:** Schematic of the model used in the finite element simulations for predicting insect stimulator interface temperature.

**Figure 3.2:** Finite element simulation results showing the maximum temperature in the PZT and the temperature at the tissue interface as a function of varying input power.

**Figure 3.3:** Ultrasonic machining for piezothermal stimulators.

**Figure 3.4:** Variation of the steady state temperature attained by the piezothermal stimulator as a function of frequency when bonded to the elytra of the beetle. The temperature variation with the input RMS voltage is also plotted.
Figure 3.5: (a) Schematic of the experimental setup used in characterizing the angle turned by the beetle. (b) Photograph of beetle turning towards left side due to actuation on right side.

Figure 3.6: Turning characterization for P3 in GJB. P3 produces an average turning of 16° at 360 mW.

Figure 3.7: Photograph of the roach turning towards its left side due to the actuation of P2 on the right side. The angle turned was characterized by positioning the roach on the paper marked with angles.

Figure 3.8: Turning characterization for P1 and P2 in roaches. Statistical variation of angle turned indicates that maximum count occurs in the range of 30°-45° per actuation at 330 mW.

Figure 3.9: Left and right turning characteristics for P2 in roaches. The behavior was statistically symmetrical.

Figure 3.10: Variation of time required for actuation of roaches with input power. As expected, the actuation time decreased with increase in the input power.

Figure 3.11: Photograph of the green diving beetle turning towards its right side due to stimulation on the left side. The arrow indicates the orientation of the GDB before and after stimulation.

Figure 3.12: Statistical variation in the response of the green diving beetle with and without thermal stimulation.

Figure 3.13: Left and right turning characteristics for P4 in green diving beetles. The green diving beetles turn about 15°-60° per actuation.

Fig. 3.14: The average temperature at the tissue-stimulator interface for different sizes of the piezothermal stimulator when the maximum temperature in the stimulator is 450 K. Simulations suggest that for diameter <130 µm, the interface temperature falls below 43°C.

Figure 3.15: Photograph of the commercially available ultra-light weight lithium ion battery.

Figure 4.1: Schematic model of various biopsy tool designs considered.

Figure 4.2: Finite element simulation results for the variation of temperature as a function of distance from the needle for the three designs for ultrasound intensity, Is = 90 W.cm-2.
Figure 4.3: Modified Butterworth Van Dyke (BVD) equivalent circuit for predicting the frequency shift in resonance due to tissue cauterization..............................62

Figure 4.4: (a) Schematic of the impedance curve of the PZT around the resonance frequency. (b) Analytical modeling results for the variation of anti-resonance frequency when the biopsy needle tip is in air, and in tissue before and after cauterization..............64

Figure 4.5: (a) Schematic diagram of the proposed biopsy tool. (b) Schematic of the cross-section view of the proposed biopsy tool.................................................66

Figure 4.6: (a) Ultrasonic machining process for PZT disc fabrication [Li06]. (b) PZT disc integration procedure for the biopsy tool.....................................................66

Figure 4.7: (a) SEM image of the tool used in the μ-USM process. (b) SEM image of the pattern transferred onto a PZT substrate using the μ-USM process. (c) SEM image of the PZT discs assembled into a recess made on the wall of a biopsy needle using μ-EDM...67

Figure 4.8: Variation of temperature as a function of direction and distance from the needle for (a) radial mode and (b) thickness mode resonances. The temperature distribution is similar in all directions for both resonance modes.........................69

Figure 4.9: Variation in the temperature generated at the surface of the needle for various (a) input voltages and (b) input power.................................................................70

Figure 4.10: Photograph of (a) top view and (b) cross section of the cauterized porcine tissue. The radius of cauterization beyond perimeter of needle was 1-1.25 mm for an input RMS voltage of 14 V.................................................................71

Figure 4.11: Measured variation, using Agilent 4395A impedance analyzer, of anti-resonance frequency and peak impedance magnitude, when a needle was in air, in tissue before and after cauterization (all at room temperature).................................72

Figure 4.12: Measured variation of anti-resonance frequency with temperature in the range used for cauterization. The fal returned to the original value at the range of temperatures from body temperature to room temperature........................................72

Figure 5.1: The block diagram of the proposed readout circuit for measurement of the resonance frequency shift of the PZT heaters due to tissue cauterization..................78

Figure 5.2: Schematic of a typical electromechanical impedance curve of a PZT element around its resonance frequency.................................................................79

Figure 5.3: Schematic of the interface circuit for actuation of the PZT heaters........80

Figure 5.4: Schematic of the circuit used in PSpice simulations..........................81
Figure 5.5: Typical output of the simulated VCO for a frequency of 5 MHz. The amplitude of the square wave generated is ≈3.3 V.

Figure 5.6: Frequency response of the eighth order Butterworth low-pass filter implemented using Sallen-Key topology.

Figure 5.7: The output of the peak detection circuit for an input sine wave of amplitude 5 V and frequency 11 MHz. The input sine wave is also shown.

Figure 5.8: The simulated variation of the input voltage to the VCO with time for a PZT resonance frequency of 8.76 MHz.

Figure 5.9: Schematic of the circuit built and tested on a PCB and breadboard.

Figure 5.10: Photograph of the PCB used in the experiments.

Figure 5.11: Photograph of the demo board used for actuation of the PZT heaters.

Figure 5.12: A sample waveform signal generated by the VCO.

Figure 5.13: (a) Screenshot of the sample signal input to the filter and (b) Screenshot of the corresponding output from the filter. The designed filter had a cut-off frequency of 12 MHz.

Figure 5.14: Measured frequency response of the designed Butterworth low pass filter for an input sine wave of amplitude 4 V.

Figure 5.15: A sample input sine wave signal to the peak detection circuit and its corresponding output.

Figure 5.16: The schematic of the BVD model resonator used in the experiments.

Figure 5.17: (a) Electromechanical impedance of the BVD resonator obtained using impedance analyzer for a C1 value of 5 pF. (b) The oscilloscope trace of corresponding signal given as input to the BVD resonator by the proposed circuit when the resonator is connected.

Figure 5.18: (a) Electromechanical impedance of the biopsy needle with embedded PZT heaters obtained using impedance analyzer. (b) The oscilloscope trace of corresponding signal given as input to the PZT heaters by the proposed circuit when the biopsy needle is connected.

Figure 5.19: A sample output signal from the PZT actuation circuit.
Figure A.1: Schematic of the SEDUS process used for patterning PZT ceramic plate. 110

Figure A.2: Schematic of the serial mode µEDM setup used for fabrication of microtools. ........................................................................................................................................................................111

Figure A.3: Schematic of the µUSM setup created for batch mode pattern transfer to ceramic workpiece. ..................................................................................................................................................................................................................111

Figure A.4: Schematic of the batch mode µEDM setup used for fabrication. 109

Figure A.4: Schematic of the batch mode µEDM setup used for fabrication of microtools. ................................................................................................................................................................................................................................................................................113

Figure B.1: Schematic of the (a) Mushroom and (b) concave shaped spherical structure fabricated using the 3D-SOULE process. ........................................................................................................................................................................................................................................113

Figure B.2: 3D-SOULE process flow diagram for fabrication of concave and mushroom-shaped spherical structures. 3D-SOULE process utilizes serial µEDM, batch mode µUSM and lapping to fabricate devices in the above mentioned shapes. This process can be applied to a wide variety of glasses, fused quartz etc. ..........................................................................................................................................................................................................................117

Figure B.3: (a) Schematic of the cross-section view of the simulated structure. (b) Simulated mode shape of the 4 node “wine glass” resonance mode. The simulated value of the resonance frequency was 1.36 MHz. ........................................................................................................................................................................................................................................119

Figure B.4: (a) USM tool for fabrication of spherical shell. (b) USM tool for fabrication of mushroom shaped structure with cavities at the center of the sphere. 121

Figure B.5: SEM image of the fabricated (a) concave spherical structure and (b) mushroom shaped structure. (c) Photograph of the top view of the mushroom structure made from transparent NBK7 glass spheres. (d) Photograph of a fabricated mushroom structure from a ruby sphere. ........................................................................................................................................................................................................................................122

Figure B.6: Resonance characteristics of mushroom-shaped structure around the 4-node wine-glass mode resonance frequency (1.379 MHz) in air. The quality factor of the resonance mode was experimentally measured at 345 in air, limited largely by anchor loss. ........................................................................................................................................................................................................................................123
LIST OF TABLES

Table 1.1: Typical values for the properties of common material used as a microheater.9

Table 2.1: Properties of the materials used in the finite element simulations.33

Table 3.1: Material properties used in the finite element simulation of interface temperature generated for various input power.44

Table 3.2: Comparison chart for different types of piezothermal stimulators used in the experiment.45

Table 4.1: Material properties used in the simulations.61

Table 4.2: Material properties used in the BVD analytical model.63

Table 5.1: PSpice simulation results of the proposed circuit for low and highly damped PZT element.85

Table 5.2: List of ICs used in the experiments.87

Table 5.3: Comparison of the experimental frequency and the expected frequency for the output signal from the VCO.89

Table 5.4: Comparison of the amplitude of the input sine wave signal and the output DC signal from the peak detection circuit.91

Table 5.5: Comparison of the calculated and experimental outputs obtained from adder, amplifier and subtractor circuits. A1 and A2 are the inputs to the adder and S1 is the input to the subtractor.92

Table 5.6: Experimental comparison of the resonance frequency of the BVD model resonator measured using the impedance analyzer and from the proposed circuit.93

Table 5.7: Experimental comparison of the resonance frequency of the PZT embedded biopsy needle measured using the impedance analyzer and from the proposed circuit.94

Table B.1: Comparison of tool wear in SS 316 and SS 440 spheres during μUSM process.120
Table B.2: Machining parameters for the batch mode μUSM process used in the 3D-SOULE process
LIST OF APPENDICES

Appendix A: PZT fabrication technologies.............................................105

Appendix B: 3D-SOULE: A fabrication process for large scale integration and micromachining of spherical structures.................................................114
ABSTRACT

This work explores the use of bulk micromachined piezoelectric transducers for ultrasonic heat generation. The work includes basic studies of the phenomenon, the development of simulation models, the design and fabrication of practical devices and interface circuits. The technology is demonstrated in two application contexts: cauterization with a biopsy needle, and stimulation of insect locomotion.

Simulations based on three-dimensional finite element models, indicate that circular disc-shaped elements provide superior steady-state temperature rise for a given cross-sectional area, volume of the PZT element, and drive voltage. The heating is greatest at the frequency of maximum electromechanical conductance. The thermal efficiency is maximized at frequency of maximum electromechanical impedance. Stacked PZT heaters provide 3.5x the temperature rise and 3x greater efficiency than single elements.

A biopsy needle with an embedded array of four piezoceramic microheaters of 200µm diameter and 70-80µm thickness has been fabricated. The PZT-5A heaters generate the target temperature rise of 33°C at the tissue-needle interface for an input power of <325 mW and a drive voltage of <17V_{RMS} when inserted into porcine tissue. The extent of tissue cauterization is <1.25mm beyond the perimeter of the needle. Cauterization of porcine tissue sample results in a decrease of 600kHz in the resonance frequency and 900ohms in the peak impedance magnitude, allowing the extent of
cauterization to be monitored easily. Interface circuits for measurement of resonance frequency shift due to cauterization and for actuation of PZT heaters are also described.

Experiments have been conducted using piezothermal stimulators implanted near antennae of green June beetles (GJB), and on either side of the thorax of Madagascar hissing roaches and green diving beetles (GDB) to show the feasibility of locomotion control using microthermal stimulation. Thermal stimulation causes the insects to move away from the direction of the actuated stimulator. Thermal stimulation achieves an overall success rate of 80%, 93.5% and 68% in GJB, roaches and GDB, respectively. On average, thermal stimulation results in an angle turn of about 15°-18° on GJB, 30°-45° on the roaches and 15°-60° on GDB. The corresponding average input power is 360mW, 330mW and 100mW for GJB, roach, and GDB, respectively.