# DESIGN AND IMPLEMENTATION OF HYBRID ACOUSTIC ENERGY TRANSFER TECHNIQUE FOR WIRELESS PACEMAKER SYSTEM

by

**MD RABIUL AWAL**
**(1540811727)**

A thesis submitted in fulfillment of the requirements for the degree of

Doctor of Philosophy

**School of Computer and Communication Engineering**
**UNIVERSITI MALAYSIA PERLIS**
2018

*To my parents.*

# ACKNOWLEDGMENT

First of all, I would like to thank The Almighty ALLAH (SWT) who gave me the permission to get another, yet the highest academic achievement of my life.

I am deeply indebted to my supervisor Dr. Muzammil Jusoh and consider myself very fortunate to work under his guidance. His expertise, enthusiasm and breadth of knowledge have worked as constant encouragement for me through the whole program. It is my privilege to express my gratitude to my two co-supervisors, Dr. Thennarasan Sabapathy and Dr. Ramlee Kamarudin. Hence, a special thanks to the advisory panel for the technical discussions and their significant contribution to the program.

I would like to thank Professor Dr. R Badlishah Ahmad, Professor Dr. Mohamed Fareq Malek and Professor Dr. Syed Alwee Aljunid Syed Junid for their courageous presence throughout the academic session.

School of Computer and Communication Engineering helped me in a various way. Nevertheless, it could not have done without the help from Assoc. Prof. Dr. Azremi Abdullah Al-Hadi and Dr. Hasliza A. Rahim. I want to express my profuse thanks to all the academic and administrative staffs of the school.

Centre For Graduate Studies (CGS) and Centre for International Affairs (CIA) have been helping me since the first day of my PhD program. I would like to thank all the staffs of the offices.

I would like to take the opportunity to thank all the colleagues of Bioelectromagnetics Research Group (BioEM) and Embedded Network and Advanced Computing (ENAC) research units. Especially, Mohd Ilman Jais, Iszaedy Bin Ismail, Amir Nazren, L Murukesan A/L Loganathan who have contributed a lot to my research.

I am indebted to the Ministry of Higher Education, Malaysia for the financial support I have been provided. I devote my warm thanks to Universiti Malaysia Perlis for giving me the chance to add another colorful feather to my life diary.

On personal level, I would like to thank Dr. Md Mostafijur Rahman for becoming my local guardian here. I would like to add Dr. Md. Rubel Basar and Dr. Md. Manjur Ahmed for their helpful discussions. In addition, I would like to mention my aunt, Dr. Sahena Ferdosh for her valuable guidance over the time.

Last but the biggest, I would like to thank my parents for bringing me to this terrible world but made it safe for me. Their life through sacrifices make my life dynamic. My father is my mentor of life and my mother is the example of simplicity. Nevertheless, I would like to apologize if I have forgotten to mention any well wisher of my work.

# TABLE OF CONTENTS

PAGE

**DECLARATION OF THESIS** i

**ACKNOWLEDGMENT** iii

**TABLE OF CONTENTS** iv

**LIST OF TABLES** viii

**LIST OF FIGURES** ix

**LIST OF ABBREVIATIONS** xii

**LIST OF SYMBOLS** xiii

**ABSTRAK** xiv

**ABSTRACT** xv

**CHAPTER 1 : INTRODUCTION** 1

1.1 Research background 1

1.2 Problem statement 5

1.3 The objectives of the study 7

1.4 Research scope 8

1.5 Organization of this Thesis 9

**CHAPTER 2 : OVERVIEW OF THE ACOUSTIC ENERGY TRANSFER (AET) TECHNOLOGIES** 12

2.1 Fundamental outline of AET. 12

2.2 Benefits of AET. 13

2.3 Review of the related past studies 14

2.4 Summary of the studies 29

2.5 Existing challenges 33

2.6 Dual Energy Harvesting Platform 35

**CHAPTER 3 : HYBRID ACOUSTIC ENERGY TRANSFER (HAET) 38**

3.1 Process flow of the research 38

3.2 Hybridization principles of energy harvesting 40

3.3 Mathematical modelling 41

3.3.1 Piezomagnetic circuit modelling 41

3.3.1.1 Case one: Considering solenoid 42

3.3.1.2 Case two: Considering permanent magnet 43

3.3.1.3 PZT circuit modelling 44

3.3.2 Classical model analysis 47

3.3.2.1 Governing equations 47

3.3.2.2 Displacements of the cantilever beam 48

3.3.2.3 Energy stored in the cantilever beam 49

3.3.2.4 Design and simulation of the cantilever 49

3.3.3 Cantilever dimension measurements 51

3.3.4 Geometric structure analysis using ideal Wurtzite Crystal Structure 55

3.3.4.1 Modelling of the cantilever 56

3.3.4.2 Crystal unit cell modelling 56

3.3.4.3 Angles between the bonds 58

3.3.4.4 Compression to the z-axis of unit cell 58

3.3.5 Expansion to the x axis of unit cell 59

3.3.5.1 Direction of deformation 60

3.3.5.2 Unit cell mass 60

3.3.5.3 Associated silicon wafer base block mass 61

3.3.5.4 Resultant force of the unit cell 62

3.3.5.5 Deformations of the acoustic medium 63

3.4 PZT receiver fabrication method 64

3.5 Fabrication process 66

**CHAPTER 4 : PERFORMANCE ANALYSIS OF THE PROPOSED AET 69**

4.1 Performance profile from mathematical modelling 69

4.1.1 Displacements in piezomagnetic circuit modelling 69

4.1.2 Displacements of the cantilever beam from classical modelling 71

4.1.3 Cantilever displacements in geometric structure analysis 71

4.1.3.1 Validation 72

4.2 Performance Analysis of the Cantilever by Finite Element Simulation 74

4.2.1 Sound pressure level 74

4.2.2 Cantilever displacement 76

4.2.3 Electric potential 77

4.2.4 Power intensity 77

4.3 Performance analysis of the fabricated cantilever 78

4.4 Transmitter design method 79

4.4.1 Dimension and transition distance of the transmitter 80

4.4.2 Available power in the receiver 81

4.5 System testing with Finite Element Analysis 82

4.5.1 Method 1: Symmetric coupled ultrasonic transducers 85

4.5.2 Method 2: Cantilever coupled ultrasonic transducer 86

4.6 System testing 89

4.7 Work Comparison 96

4.7.1 Frequency 96

4.7.2 Medium 97

4.7.3 Separation distance or depth 97

4.7.4 Output power 97

4.7.5 Efficiency 98

**CHAPTER 5 : CONCLUSION AND FUTURE WORKS 101**

5.1 Conclusions 101

5.2 Future works 103

**REFERENCES 105**

**APPENDIX A PULSE GENERATOR FOR 5V POWER SUPPLY 119**

**APPENDIX B PUBLICATIONS FROM THIS WORK 120**

# LIST OF TABLES

| NO. | | PAGE |
|---|---|---|
| Table 1.1: | Power descriptions for various implantable biomedical devices (IMDs), including wired and wireless. | 2 |
| Table 2.1: | Deployment of the existing AET systems (1985-2015). | 30 |
| Table 2.2: | Summary of the review. | 31 |
| Table 2.3: | Comparison of WPTTs. | 31 |
| Table 3.1: | Cantilever Dimension Descriptions. | 51 |
| Table 3.2: | Cantilever dimensions and displacement descriptions. | 54 |
| Table 3.3: | Unit cell mass of the deposited Al-ZnO | 60 |
| Table 3.4: | Cantilever dimension descriptions | 61 |
| Table 3.5: | Parametric device descriptions. | 64 |
| Table 4.1: | Cantilever dimension and deformation descriptions. | 72 |
| Table 4.2: | Cantilever deformation validations. | 73 |
| Table 4.3: | Device comparison. | 79 |
| Table 4.4: | Human Chest Phantom Design. | 84 |
| Table 4.5: | Transmitter receiver parametric descriptions. | 84 |
| Table 4.6: | Specification of the used ultrasonic transducers. | 88 |
| Table 4.7: | Comparison between the methods | 96 |
| Table 4.8: | Comparison with the exisitng literatures | 99 |

# LIST OF FIGURES

**NO.** **PAGE**

Figure 1.1: Research scope flow. 9

Figure 2.1: Fundamental Schematic of an AET System. 13

Figure 2.2: 1kW power transfer through metal wall. 27

Figure 2.3: 88% Efficiency is achieved, transmitting 1kW of power. 28

Figure 2.4: Achieved 1m seperation distance. 28

Figure 2.5: Efficiency vs. Separation Distance. 32

Figure 2.6: Frequency vs. Received Power. 32

Figure 2.7: Summary of the Existing AETs. 32

Figure 3.1: Research flowchart. 39

Figure 3.2: Illustration of the proposed hybrid energy harvester. 40

Figure 3.3: Working principle of the proposal in magnetic strategy. 40

Figure 3.4: Working principle of the proposal in acoustic strategy. 41

Figure 3.5: Modelling of the Cantilever. 47

Figure 3.6: Cantilever Descriptions (a) Cantilever Materials (b) Cantilever Meshing. 50

Figure 3.7: Dimensions of the proposed cantilever (in mm). 50

Figure 3.8: Maximum displacements of the cantilever for cases 1 - 8. 53

Figure 3.9: Maximum displacements of the cantilever for cases 9 - 10. 54

Figure 3.10: Al doped ZnO unit cell. Here, $\alpha = \beta = 109.47^o$;$\gamma = 141.06^o$; $l_{ZnO} = 1.9757Å$, $l_{AlO} = 1.8Å$ is considered. 56

Figure 3.11: Fabrication process of the cantilever (a) SOI wafer preparation, (b) etching, (c) PZT layer deposition, (d) top electrode deposition, (e) bottom electrode deposition and the released beam. 65

Figure 3.12: Fabricated cantilever ($70 \times 10 \times 0.5009$ mm$^3$) 66

Figure 3.13: Microscopic photograph of the deposition layers, deposited aluminum surface (top), ZnO and Al layers of the cantilever (bottom). 68

Figure 4.1: Displacement of the plate vs. output power. 70

Figure 4.2: Device displacements from classical analysis. 71

Figure 4.3: Resultant expansion of the cantilever length. 72

Figure 4.4: Unit cell deformation towards cantilever length. 73

Figure 4.5: Cantilever Pressure Details (a) Sound Pressure Level (SPL) (b) Scattered SPL (c) Far Field SPL (d) Total Acoustic Pressure Field (e) Far-Field Pressure (f) Far Field SPL. 75

Figure 4.6: Cantilever Displacement Details (a) Total Cantilever Displacements (b) Cantilever Displacements (c) Cantilever Stress (d) Electric Potentials (e) Cantilever Intensity magnitude (f) Cantilever Elastic Strain Energy Density. 76

Figure 4.7: Finger pressure generated voltage (open load mode). 78

Figure 4.8: Finite element analysis of AET using PZT diaphragm plate (a) Transmitter view (b) Model meshing. 83

Figure 4.9: Finite element analysis of AET using PZT diaphragm plate and rectangular cantilever (top) transmitter receiver view (bottom) Model meshing. 83

Figure 4.10: Method 1: Performance of the AET in terms of wave parameters. 85

Figure 4.11: Method 2: Performance of the AET in terms of wave parameters. 86

Figure 4.12: Sound pressure level received by the PZT receiver. 87

Figure 4.13: Received SPL profile, (a) on bottom electrode (layer 5) (b) on PZT layer (layer 4) (c) on silicon layer (layer 3) 88

Figure 4.14: Arduino Uno Rev3 is used as the controller. 89

Figure 4.15: Ultrasonic transducers (without matching layers). 89

Figure 4.16: Experimental setup for dual ultrasonic transducer. 90

Figure 4.17: Test 1: Open medium, open load. 91

Figure 4.18: Test 2: Interference contained medium, open load 91

Figure 4.19: Test 2: Closer setup image 92

Figure 4.20: Test 3: Experimental setup for cantilever coupled ultrasonic transducer (top view) 93

Figure 4.21: Test 3: Closer look to the experimental setup 93

Figure 4.22: Test 3: Open medium, open load 94

Figure 4.23: Test 4: Interference contained medium, open load 94

Figure 4.24: Experimental set up with fat layer 95

Figure 4.25: Test 5: Experiment with fat layer 95

# LIST OF ABBREVIATIONS

| | |
|---|---|
| IMD | Implanted Medical Devices |
| WPTT | Wireless power transfer technology |
| AET | Acoustic energy transfer |
| HAET | Hybrid Acoustic energy transfer |
| EMAT | Electro-magnetic acoustic transducers |
| SoC | System-on-Chip |
| EBPVD | Electron beam physical vapor deposition |
| KOH | Potassium hydroxide |
| SPL | Sound pressure level |

# LIST OF SYMBOLS

| | |
|---|---|
| L | Solenoid length |
| W | Wireless power transfer technology |
| AET | Acoustic energy transfer |
| N | Number of turns of Solenoid |
| A | Cross-sectional area |
| I | Applied current on Solenoid |
| $B_0$ | Magnetic flux density |
| $R_C$ | Coil resistance |
| Z | Relative velocity of piezo plate |
| $R_L$ | Loading resistance |
| $\Omega$ | External vibration frequency |
| $\omega_0$ | Natural frequency of the system |
| Y | Amplitude of vibration |
| Z | Total damping ratio of the system |
| Å | Angstrom |
| P | Density |
| $\mu_0$, K | Magnet, and Spring constant |
| $\Lambda$ | Wavelength |
| $\Phi$ | Phase angle |
| $K_e$ | Stiffness of the piezoelectric plate |
| $C_p$ | Capacitance of the piezoelectric plate |
| $L_p$ | Inductance of the piezoelectric plate |

# Reka Bentuk dan Pelaksanaan Teknik Pemindahan Tenaga Akustik untuk Sistem Pacemaker Tanpa Wayar

## ABSTRAK

Peranti bioperubatan berskala mini mendapat tumpuan pihak industri kerana sifat geometrinya. Di samping itu, peranti ini mempunyai fungsi yang lebih baik dari segi jangka hayat yang lebih lama dan sumber kuasa yang boleh dipercayai terutamanya untuk peranti yang diimplan. Walau bagaimanapun, peranti yang menggunakkan bateri untuk mengaktifkan system memerlukan kos yang lebih tinggi, berukuran besar untuk diimplankan, tiada keupayaan untuk dicas semula dan memerlukan penyelenggaran yang kerap. Oleh itu, penyelidikan tentang sistem tanpa bateri aktif dijalankan sejak dua dekad yang lalu. Untuk mengatasi masalah ini, teknologi pemindahan kuasa tanpa wayar *(WPT)* telah dicadangkan dalam situasi sebenar. Sehingga kini, 4 modul *WPT* telah diterima dan berfungsi iaitu, Induktif *WPT*, Kapasitif *WPT*, Optik *WPT* optik dan Akustik *WPT (AET).* Walaubagaimanapun, *WPT AET* mengalami masalah dari segi isu keselamatan atau isu prestasi kerana *AET* sendiri dipengaruhi oleh beberapa parameter yang menjejaskan prestasai sistem. Penyelidikan ini mencadangkan pendekatan berdasarkan kaedah penyebaran tenaga akustik untuk menyalurkan kuasa kepada peranti implan secara tanpa wayar. Sistem yang dicadangkan digerakkan oleh pasangan peranti piezoelektrik, yang bertindak sebagai pemancar dan penerima. Sumbangan utama kerja ini adalah kepada penggunaan platform peranti yang sama untuk dua skim penuaian tenaga, seperti akustik dan elektromagnetik. Ia dipanggil, AET hibrid (HAET). Di samping itu, simulasi dada manusia dibentangkan untuk mengesan kesan dari medium penyebaran lapisan berganda. Beberapa parameter boleh dianggap sebagai kriteria penilaian; seperti menerima kuasa, kekerapan operasi, geometri peranti, jarak pemisahan adalah tumpuan utama dalam kajian ini. Oleh itu, mereka dibincangkan secara terperinci dengan beberapa analisa yang berunsur terbatas, termasuk analisis model klasik, deskripsi vektor dan simulasi bantuan komputer. Akhir sekali, reka bentuk telah diuji dalam persekitaran yang sebenar untuk pengesahan pasca fabrikasi dan pembuktian konsep pencirian. Dimensi peranti penerima yang dipilih adalah 20 × 10 × 0.62 $\text{mm}^3$. Dari pemodelan matematik dan analisa, didapati bahawa HAET yang dicadangkan boleh menghantar kuasa 2 mW kepada penerima di alat pacu jantung. Di samping itu, kecekapan yang dicapai ialah 2.77% adalah lebih baik berbanding dengan kebanyakan literatur yang ada. Walau bagaimanapun, penyelesaian untuk parameter pantulan akustik dan ketidakpadanan impedans untuk medium lapisan berganda adalah masih menjadi cabaran. Walau bagaimanapun, impak penerimaan penuaian tenaga di degupan jantung adalah tidak dinilai dalam kajian ini.

# Design and Implementation of Acoustic Energy Transfer Technique for Wireless Pacemaker System

## ABSTRACT

Miniaturized biomedical devices have drawn significant industrial attention due to their convenient geometry. In addition, these devices have improved and continuous functionality with longer lifetime, and reliable power supply, especially for implanted devices. However, they contain batteries in order to activate the systems, which is bulky, cost inefficient, not rechargeable and need frequent replacement. Hence, removing the battery from the system has been an active research area for last two decades. To resolve, wireless power transfer (WPT) technology has been proposed in real practice. So far, WPT has adopted 4 modules to function, namely, inductive WPT, capacitive WPT, optical WPT and acoustic energy transfer (AET). All but AET, suffer from the safety or performance issues. However, AET itself is influenced by several parameters which results affected system performances. Consequently, this research work proposes an approach based on the acoustic energy propagation method to deliver power to implantable devices wirelessly. To do so, the proposed system is actuated by the pair of piezoelectric devices, which are the transmitter and receiver. The main contribution of the work relies on the use of same device platform for two energy harvesting scheme, acoustic and electromagnetic. It is called, hybrid AET (HAET). In addition, a simulated human chest phantom is presented to investigate the impact of multilayer propagation medium. Several parameters can be treated as the evaluation criteria; however, received power, operating frequency, device geometry, separation distance is mainlyfocused mainly in this research. Hence, they are addressed in detail with several finite element analysis, including classical model analysis, vectorial descriptions and computer aided simulations. Lastly, the design is tested under real environment for post fabrication verification and proof-of-concept characterization. The receiver device dimension is selected as 20×10×0.62 mm$^3$. From the mathematical modeling and the finite element analysis, it is found that, the proposed HAET can deliver 2 mW power to the receiver end in the pacemaker. In addition, the achieved efficiency is 2.77% which is better compared to most of the existing literatures. However, the solution for acoustic reflection coefficient and impedance mismatch for a multilayered medium is still a challenge. Additionally, the impact of the heartbeat on the receiving energy harvesting is not considered in this research.

# CHAPTER 1 : INTRODUCTION

## 1.1 Research background

Recently, rapid progresses are seen in the art of health care monitoring systems. Instead of relying on the eyes or analogue routine check, health care industry now depends on the medical technology. This technology offers devices that can monitor health status by using wired or wireless technologies that can be worn or be implanted in the body. Among these, implanted devices have drawn significant attention in the health care industry due to the ease of application, since the first implantable heart pacemaker of 1958 (Hemel & der Wall, 2008). They are referred as implanted medical devices (IMD). IMDs can measure a number of physiological parameters and can take necessary actions according to the control protocols. For instance, Sensory and neurological implants are used for senses, brain and other neurological disorders and treat the conditions of the visual impairments; hearing loss issues and neurological diseases. Cardiovascular medical devices can measure heart conditions and trace heart failure, cardiac arrhythmia, ventricular tachycardia, valvular heart disease, angina pectoris, and atherosclerosis and can control in absence of proper rhythms. Additionally, there are some more to monitor hypertension, provide functional electrical stimulation of nerves, operate as glaucoma sensors, and monitor bladder and cranial pressure (McLatchie, Borley & Chikwe 2013). In addition, they are cost effective, user friendly and more reliable. Hence, it is not far when the improvement of the IMDs will reach a level of intense development and miniaturization. In fact, it is expected that, within a short time IMDs will be able to monitor or control nearly every bodily function and movement with minimal cost and advanced technologies (Lau, Siu, & Tse, 2014).

Though the advancements of the IMDs have make them dependable devices for long term biological monitoring, however, powering them has been a difficult challenge. Conventional powering allows IMDs to be powered through batteries, either external or internal. For external powering, the power source is located outside of the patient body while the operating device is implanted inside. The power is delivered by a connecting wire to both sides, hence, it is painful and very uncomfortable. However, the total device system including power source and operating device are implanted for the latter method. For both cases, it requires a bulky battery which enables the device functions. Nevertheless, a painful long surgery is required to implant the device. Therefore, this solution is expensive, uncomfortable as well. In addition, they possess additional weight and inconvenient geometry to the device. On top of everything, this process has to be repeated within five to ten years over and over for further smooth activation of the device since the battery is charge limited. These factors may result a life risk and/or at least health degradation. A feasible solution of these addressed problems is the wireless power transfer technology (WPTT) for the IMDs. Table 1.1 gives some power information for the IMDs (Wei & Liu, 2008; Rasouli & Phee, 2010; Szczesny, Jetzki, & Leonhardt, 2006).

Table 1.1: Power descriptions for various implantable biomedical devices (IMDs), including wired and wireless.

| **Biomedical devices** | **Power descriptions** |
|---|---|
| Biomonitoring system | <100 μW |
| Pacemaker | 10-100 μW |
| Cochlear processor | 200 μW |
| Hearing aid | 100 μW-2 mW |
| Drug delivery pump | 100 μW-2 mW |
| Neural recorder/stimulator | 1-100 mW |
| Implantable mechanical actuator | 40 mW |
| Cardioverter-defibrillator | <100 μW (standby)<br>5-10 W (peak) |
| LVAD (left ventricular assist device) | 10-100 W |
| TAH (total artificial heart) | 10-100 W |

Since 2000, the development of WPTT has been continued by means of serious research. Now, WPTT is an active area for both research and commercial centric approach. WPTT offers several benefits over the conventional systems, such as, cord and battery elimination, connector removal, integration of application boundary, modificationless system extension and more. Hence, WPTTs are considered as a promising future oriented industry. In fact, in a recent work, it is focused to charge 30 smart phones (1 *W*) or five laptops (2.4 *W*) simultaneously within 50 *cm* surrounding wireless area. This experience indicates the rapid development trends of WPTTs (Gozalvez, 2015).

WPTT has four active branches so far. Namely, inductive, capacitive, microwave and acoustic WPTT. Additionally, optical WPTT is emerging as a subclass of electromagnetic WPTT. Among all these, inductive WPTT (IPT) is widely practiced and commercially available (Wei, Wang & Dai, 2014). This WPTT is enriched with high efficiency, high power (30 kW) and relatively long-distance power transfer capability. Recently reported that, 5 to 7 meter separation distance between receiver and transmitter is achieved by IPT (Park, et al, 2015). Though IPT offers several benefits, however, the increment in the separation distances reduces the system efficiency linearly. In addition, the penetration losses of IPT for in-vivo medium is more drastic than the air medium (Basaeri, Christensen, & Roundy, 2016). Moreover, IPT suffers from the transmitter-receiver coupling misalignment.

Acoustic energy transfer (AET), transfers power by propagating energy as sound or vibration waves. The propagated energy then collected by a receiver which converts the vibration energy to useful electrical energy. To do so, an ultrasonic or piezoelectric transducer is used as the power transmitter in terms of acoustic vibrations. The transmitter is operated by some relative frequencies. The range of operating frequency may vary from kHz to MHz, based on the applications. On the receiver side, usually a piezoelectric receiver is set to collect the acoustic effects. These effects cause a deformation in the piezoelectric layers of the receiver and induce an electric potential which can be collected and stored. This conversion is termed as piezoelectricity and it is the working principle for AETs. AET is applicable in various wireless energy platforms. However, two applications can be mentioned as they are already in the line of commercial product, wall through (usually metal) and air through energy transfer.

Optical WPT can provide very high efficiency and wide propagation area due to their high energy density penetration. In practical, the propagation area can reach long range (more than km). Hence, highly recommended for distance energy transmission. However, optical WPT can offer 40-50% efficiency because of its two step conversion process. In addition, the energy is available only in the narrow transmission axis. The energy transfer is also affected by the presence of interference in line of sight (Cai & Vahala, 2000).

Capacitive WPT, on the other hand, is still in the developing stage of research and development. Unfortunately, the inverse property of capacitance with respect to distance, limits the separation and efficiency of this WPT. However, for short distance (<1 mm) it can achieve high power (>1 kW) transfer with reasonable efficiency (Theodoridis, 2012).

As it is already mentioned that, inductive and acoustic WPTTs are the most promising in the context of efficiency and separation distances. Hence, from this motivation, it is intended to design a hybrid WPTT by achieving the inductive-acoustic, i.e. magnetic and piezoelectric combination. The benefit of this combination is the smaller device geometry as two energy transaction is located on the same device platform. Again, dual function of a system increases the robustness of the system which also benefits the device reliability. Hence, the benefits can be summarized as:

- Smaller device size
- Increased robustness, hence, more reliable

## 1.2 Problem statement

From the aforementioned discussions, it is clear that, as standalone, both inductive and acoustic WPT suffers from several performance issues. Namely, transmitter receiver separation distance, system efficiency, safety regards for in-vivo medium, lower robustness and hence affected system reliability (Sanni, Vilches, & Toumazou, 2012, Dzialoshinskii, 1958).

The transmitter receiver separation distance depends on the location of the IMD inside the body. For the implantable pacemaker, usually the separation distance varies from 50 mm to 70 mm depending on the fat layer under the skin. To compensate, the distance is increased to 70 mm, as the chest skin to heart distance is in apical 31.3 +/- 11.3 mm (Rahko, 2008). At this point of view, both IPT and AET can deliver required power to the receiver within that transmission distance. However, IPT possesses lower efficiency compared to that of AET for the in-vivo medium, i.e. the propagation losses are too high for the implants. On the other hand, AET has better propagation efficiency for implants. Hence, for in vivo environment, the combination of a dual energy harvesting system can achieve improved system efficiency as a hybrid energy transfer system (Meng & Kiani, 2017).

Long term exposure of the IPT or AET is not recommended for in-vivo environments, as the impact is not confirmed yet. The inverse effects are mainly due to the higher energy penetration to the transmitter. However, for a dual system, the required input energy is splitted, hence, the inverse impact is reduced naturally.

Single or mono-techniques are less robust by nature, as it is a single input single output (SISO) system. However, a combined or hybrid platform can have multiple inputs with a combined single output and is called multiple inputs single output (MISO). With multiple output options, it is called MIMO. A MISO is more robust than that of SISO due to the multiple input options on a single platform. Now, very few literatures are found on the MISO to be applicable for wireless power applications. However, several hybrid models based on electromagnetic and piezoelectric interaction are available to harvest ambient RF and vibration energy which can be tagged as MISO. Nevertheless, these models are not actually hybrid, rather, they are just the assembly of two distributed models. Therefore, the system efficiency is affected by noticeable margin due to the two step energy conversion process. In contrast, a dual system on the same device platform can improve the system performance while using smaller device size. In addition, High performance devices cause very complex and expensive design and fabrication procedures by nature (Charthad et al., 2015). However, low cost receiver is required in order to reduce the system cost. Hence, the problem statements can be summarized as:

1. As standalone, both inductive and acoustic WPT suffers from lower robustness and reliability. However, the integration of them is advantageous in terms of system efficiency and robustness.

2. The long term exposure of the conventional WPTs have inverse impact, mainly due to the high power electromagnetic radiation. However, the low power IPT and AET reduce those impact.

3. Dual conversion system for a MIMO system, has lower efficiency and higher energy consumption. However, a MISO provides improved efficiency and energy consumption.

## 1.3 The objectives of the study

From the discussions in the previous section, the objectives of this research are set as follows:

1. To model and simulate a new integrated hybrid WPT based on inductive and acoustic energy transfer system which works on a single platform.

2. To achieve chest to heart separation distance by the transmitter and receiver with minimum >10 μW received power by the receiver through a five layer human chest phantom composed of skin, fat, muscle, bone and liquid layers. Additionally, existing power transfer system efficiency for in vivo environment lies within 2%. Hence, improved system efficiency is focused in this work.

3. To develop a compact receiver for the hybrid energy harvesting scheme with reduced fabrication cost and fabrication process.

## 1.4 Research scope

Research is a limitless process in the context of scope. A research scope can be extended to multiple dimensions. However, several parameters bound the research to be scope limited (e.g. time, unavailability of resources). Hence, this research is focusing to the following scope,

1. Introduction of an acoustic based WPTT for internal pacemaker system. The architecture and implementation will be presented in detail.
2. Finding the best suitable methodology to implement in order to achieve optimum performances.
3. Mathematical and simulation analysis to achieve commercial centric fabrication quality.
4. Finding suitable device geometry to accommodate the system in vivo environment.

Figure 1.1 illustrates the general research scope approach for this work. The scope includes, the hybridization of the conventional wireless transfer with a dual energy harvesting platform. A diaphragm-cantilever approach is suggested with a multi-layered piezoelectric receiver with dual electrodes.

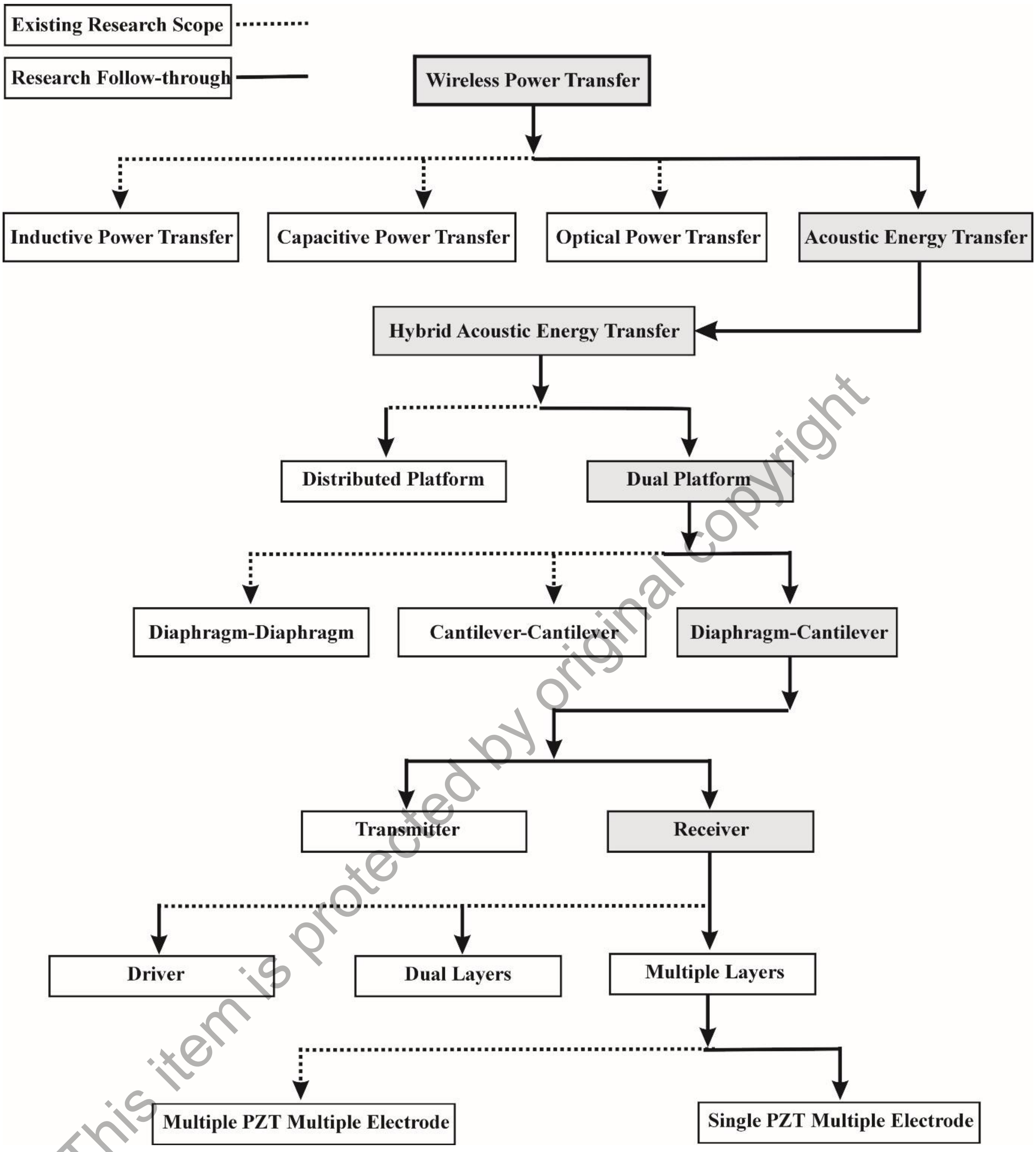

Figure 1.1: Research scope flow.

## 1.5 Organization of this Thesis

This chapter describes the overview of the existing problems in AETs for implantable devices, specially for the wireless pacemaker system. The corelated factors