ALEX HAGEN

PIEZOELECTRIC ENERGY CONVERSION FOR POWERING OF SENSORS

Project #5 - Final Report

NUCL 563

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Abstract

Sensors for many different measurements have been developed and deployed almost universally in the recent decades. These sensors can increase quality of life, monitor industrial processes, indicate health problems, or guard against engineering faults. Along with these sensors comes a high requirement for power delivery, and battery technology has grown to keep up with the power requirements. However, when considering systems where sensors must be small and lightweight, or are impossible to service[1], battery technology fails. In this void, power delivery and power harvesting have been developed. Power delivery is the use of a transmitter to send power from a relatively large base station attached to mains power to a small remote boards, which then converts the power into useful products. This type of system is the object of research for this project. Power harvesting uses ambient power to convert on a small remote board and then uses that power for useful actions.

Specifically, this project seeks to replicate the energy harvester developed by Botteron [2] with some small twists. The energy harvester proposed by Botteron is a canteliever type piezoelectric energy harvester coupled with a solar cell, both powering a temperature measurement device and ultra-wideband information transmitter. The project proposed here will remove the solar component of the energy harvester, and will convert the canteliever type piezoelectric energy harvester to a unimorph non-cantiliever type. Then, a base station will be used to deliver power into the area surrounding the sensor, which will harvest the energy and power the thermistor and UWB transmitter. Goals for decreased area, and 34$\times$ increase power are described.

This project also seeks to compare this methodology to that of other wireless power transmission, specifically WPT (or electromagnetic wireless power transmission), microwave beaming, thermal energy transfer, and plasma channel coupling.

[1] servicing of batteries includes replacement and charging

Introduction

Project Statement

Sensors of all sorts have become omnipresent in our current culture, from smart thermostats to heart rate fitness monitors. With this omnipresence comes the need for more flexible, less invasive, and wireless operations of sensors. One main barrier to the flexibility and wireless operations of sensors is the need for power delivery.

A group of researchers has generated a miniature cell conductivity sensor using a piezoelectric grain for ultrasonic wireless power delivery[18]. These sensors in particular use the power delivered through the piezoelectric grain to both measure conductivity and to operate a CMOS component that will operate as a full-bridge rectifier. Communication is then done via "backscatter", or passive, radiofrequency communication.

The concept of piezoelectric power delivery is interesting and novel, and for the application proposed by Seo, more efficient than alternatives. I propose a further investigation into the application space of this type of power delivery.

In order to properly investiage the application space, first the parameters required for efficient and worthwhile application must be explored. This involves comparing piezoelectric delivery to its competitors in terms of:

- distance to receiver
- size of receiver
- efficiency of delivery
- power needed by receiver
- intervening material
- delivery frequency

Then, depending on the results of the investigated application space, particular applications should be identified. Of interest to me are the application of piezoelectric power delivery in vibration sensing, flow visualization, or temperature recording applications.

The specific goal of a design is to match and improve the design by Botteron [2] by converting the design from a passive energy harvester, to an actively provided acoustic energy harvester. The temperature measurement proposed by Botteron will first be replicated, however the solar component will be removed, the piezoelectric component will be converted to high frequency and non-cantilievered. Then, an attempt to decrease the area of the harvester, and to increase the power to allow for 1Hz data transmission will be targeted. Finally, an attempt to attach a second piezoelectric to the system to measure vibration and report this back will be undertaken. Specific values for power needed, area, and other parameters are provided in the bulleted list below.

Goals and Objectives

As requested, I have identified several static goals, and the first set of dynamic objectives for the project:

Goals:

- To identify all currently developed sources of wireless power delivery.
- To identify largest 5 engineering requirements for wireless power delivery choice.
- To compare acoustic power delivery to PZT in the 5 above parameter space.
- To choose parameter space where acoutic power delivery is best suited.
- To generate an application within this parameter space.
- To propose a design or schematic for acoustic power delivery to pzt in the above application.

Thus, the first **objectives**, and their partially met answers are:

- Identify other developed sources of wireless power delivery.
  - Evanescent coupling (inductive coupling)
  - Power beaming[2]
  - Thermal energy transfer
  - Plasma channel coupling

[2] proposed in "space elevator" application

- Develop working understanding of physical principles behind the above wireless power delivery schemes
- Identify the largest 5 requirements for wireless power delivery
  - distance
  - targeting
  - intervening media
  - receiver size
  - power provided
  - transmitter size
- **Develop an active piezoelectric power system to take measurements and transmit them via ultra wideband radio, as in [2].** A starting design for the sensor configuration can be seen in Figure 1.

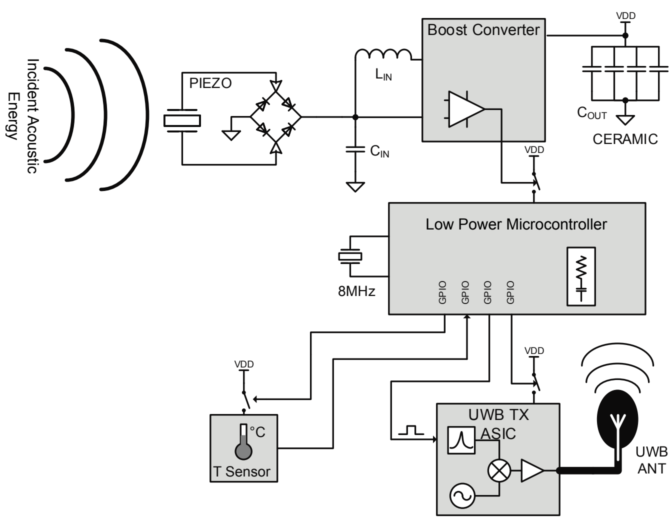


Figure 1: Sensor Design (reproduced and edited from Botteron [2] without permission)

  - **Match or increase requirement for** $12.6\,\mu$W **for one readout every** 34s
  - **Decrease size because of removed requirement of solar cell and cantileiver type piezoeolectric harvester (less than** 85×25mm^2**)**
  - **Determine if same structure can be used to take readout of separate piezoelectric vibration sensor**[3]

With these goals and objectives, a Quality Function Deployment Chart has been developed.

[3] The concern is that current will be required to convert charge generated in the piezoelectric vibration sensor before it can be read in an analog to digital converter (ADC)

Table 1: Example Quality Function Deployment Chart for a Vibration Sensor

	Technical Requirements							Ranking				
	Efficiency	Range	Targeting	Intervening Media	Transmitter Size	On Board Power	Receiver Weight	1	2	3	4	5
Evanescent Coupling												
Power Beaming												
Thermal Energy Transfer												
Plasma Channel Coupling												
Acoustic Power Transfer												
Target Values	$> 15\%$	50cm	$> \frac{\pi}{2}$sr	Fluid, Glass, Plastic	$< 85 \times 25\text{mm}^2$	$\geq 12.6\,\mu$W (target of 0.4mW)	< 1kg					

Assumptions and Constraints

The assumptions and constraints required to make a design of an active piezoelectrically powered sensor system are multiple. The most important, however, is the assumption of the medium in which the sensor must receive power. The acoustic impedance of media are vastly different, with air having a low value compared to liquids, and solids. To decrease the degrees of freedom in the design project, the media targeted will be air and water. I will also constrain my piezoelectric material choice to bulk polycrystaline lead zirconate titanate (PZT) to ensure simplicity and only optimize the circuit, shape, and size of the piezoelectric. I will use the UWB antenna developed by Botteron, but I will allow myself to use inductance to tune the system. Finally, I will assume some directionality of the transmitter, as demonstrated in the QFD chart, assuming that the transmitter will be pointed at the reciever to within one quadrant.

Literature Review

A salient feature of modern life is the use of myriad connected devices. These devices, often considered the "Internet-of-Things", are power hungry, mobile, and sensor laden. While historically, power has been supplied using batteries, the ever-decreasing size of these devices and their connected sensors desire alternative energy delivery methods. These methods can be classified as energy harvesting, or as wireless power transfer - the focus of this project. Energy harvesting and wireless power transfer have many challenges for overcoming batteries, as Table 2 shows.

Table 2: Energy densities for different energy harvesting methods - all taken from [20] except for the battery power density, calculated from [1]

Harvesting Method	Power Density
Batteries (Ni/Zn)	$840 {}^{mW}/_{cm^3}$
Solar Cells	$15 {}^{mW}/_{cm^3}$
Piezoelectric	$330 {}^{\mu W}/_{cm^3}$
Electrostatic	$116 {}^{\mu W}/_{cm^3}$
Thermoelectric	$40 {}^{\mu W}/_{cm^3}$

There is a several order of magnitude difference in the power density of "harvesting" sources and batteries. However, the ability to reduce the total volume or total mass of a system still makes energy harvesting interesting [20].

Wireless Power Transfer (hereafter WPT) is a close relative of energy harvesting in that the receiver technology is the same, but the energy to be harvested is actively supplied to the system. The idea for WPT has been around for decades, with early variants starting with the advent of antenna based wireless communication systems [16]. However, publication did not occur in earnest until the early 2000s. There are many variants of WPT, just as there are many variants of energy harvesting. Of interesting to this analysis are the topics of piezoelectric energy transfer, inductance coupling wireless power transfer, beaming - whether microwave or visible light, and induced thermal energy transfer. Plasma charge coupling was targeted previously to the literature search, but its requirement for $30 {}^{kV}/_{cm}$ is not suitable for typical applications [9].

Piezoelectricity, discovered by the Curie brothers in 1880 [5], is the property of some, asymmetric crystals to generate electricity when force is applied to them, and conversely to generate force when electricity is applied to them. The second application found many early applications in sonar and other sound related fields, including submarine detection in World War I [12]. In the intervening years between 1920 and 2000, many improvements to piezoelectric materials were made, particularly to Lead-Zirconate Titanate (hereafter PZT).

However, starting in the early 2000s, the idea of using PZT to actively harvest power was explored. In fact, high efficiencies were attained [4] for energy harvesting. This property then evolved in the subsequent years to an active power transfer method, with a specifically interesting method being miniscule "dust" to receive ultrasonic vibration and convert it into electric power to communicate signals from inside a human body [18]. Piezoelectric power transfer has several benefits, as shown through this literature review, namely that it is highly efficient, the energy transfer method can be tailored to different media, and the response can be easily modeled using the constitutive equations of PZT material, and acoustic transport through the intervening media [15, 21].

[4] up to 35% in 2004[19]

In recent years piezoelectric power harvesting has focused mainly on the applications and attached harvesting circuits involved. As described by Priya and coauthors, many of the piezoeolectric concerns with regard to shape, size, and material of the piezoceramic have been solved [17]. However, the attachment of these harvesters into circuits used to power sensors or others is non-trivial. Wang developed correlations for the dimensionless resonant harvested power versus dimensionless resistance of a circuit [24] in a single degree of freedom system. Even Priya provided the efficiency of these circuits when placed in unimorph or bimorph configuration and connected in parallel or series [17].

Other recent work has focused on applications of piezoelectric harvesting. Brach applies harvesters in canteliever configuration to "multi-modal" structures, demonstrating the applications in non-resonant systems [3]. Her contribution is the inclusion of an inductor to tune the piezoelectric resonance to the resonance of the structure, thus increasing the response with a wider range of frequencies available. Tao and coauthors continued development of a piezoelectric wind turbine, showing the macromechanical applications of piezoelectrics, with a power of up to 150W [22]. Of particular interest to this project is the recent publication by Botteron. He creates a wireless sensor node with an ultra-wideband transmitter and a printed antenna. The cantilever type piezoelectric harvester is used in conjunction with a solar cell to provide enough energy for the 12.6 μW transmission requirement [2].

The competitors to piezoelectric energy transfer are power beaming and inductance coupling energy transfer. Inductance coupling energy transfer is the logical extension of the concept of signal transmission via antenna [16]. With sufficient inductance coupling, the response of the receiving antenna can be high enough to provide actual usable current. This method is commonly used now in commercial devices to provide standoff charging. There are many methods of achieving this, whether matching magnetic resonance or through matching inductance of the transmitter and receiver [26, 25, 27]. These systems have the benefit of direct electricity transmission, but have the detriment of intervening media sensitivity, directionality, and transmission $\propto \frac{1}{r^4}$. Currently, they are used for close field charging of personal electronic devices, but the possibilities for extension are in commercial consideration, such as "Witricity" for charging in coffee shops and other public access locations [7].

Power beaming is a technology field used for longer range power transfer. Again, the system uses a directional beam of energy - delivered by either microwave or milimeter wave, or even laser pulses - to be sent to the receiver [11, 10]. The systems again have the disadvantage of directionality and intervening media sensitivity. These systems, though, are able to transfer over very large distances, with attenuation of the wave only $\propto \exp\left(-\mu r\right)$ where μ is an attenuation constant, which can be very low in air. They can calso provide large amounts of energy, which has made them of interest for space programs [6, 14, 10].

The technologies discussed in the above paragraphs, along with thermal energy transfer, will be reviewed in a combinatorial space: through 4 continuous variables and with differing intervening media (a discrete variable). Then, a region of this combinatorial space will be evaluated for a standoff temperature and vibration sensor, and an extension to the state of the art sensors will be proposed.

Results

The Design

Any acoustic system is a resonant system. When coupling the acoustic media of power transfer (air or water) with the piezoelectric transducer and a circuit, the system becomes triply resonant. The matching of the three resonances (acoustically, piezoelectrically, and electrically) becomes the prime factor for operation of a power harvester. The process of matching these resonances was carried out iteratively, with the iteration steps being:

1. Choice of PZT material and shape
2. Choice of frequency range for design
   (a) Calculation of PZT size from frequency range
   (b) Verification of PZT resonances using finite element multiphysics modeling
   (c) Verification of PZT resonances using integrated circuit modeling
   (d) Design of resonant circuit for **real** resonances from modeling software
      i. Design of *LC* circuit to match frequency of resonance
      ii. Design of *RC* circuit to match frequency of resonance
      iii. Comparison and choice between *LC* and *RC*
   (e) Simulation of power output in SPICE

This listing of steps informs the process for chaging any of the parameters. Apparently, a full scale optimization would constitute iteration through a matrix of PZT materials, PZT shapes, PZT sizes, PZT resonant frequencies from modeling, LC scaling and RC scaling. This also does not take into account the power conversion integrated circuit. This full scale optimization of a 6-dimensional combinatorial matrix is beyond the scope of this analysis. In order to reduce the degrees of freedom, assumptions have been made:

- A single PZT material and shape can provide sufficiently high results
- **Real** resonances only occur in the PZT when the FEM simulation and circuit simulation match

These assumptions significantly reduce the parameter space that must be analyzed and make this optimization much more tractable.

PZT Choice

PZT-5A (also called Navy PZT II) in a disk shape was chosen because of the common availability of the material and the information concerning the material. Channel Industries, Stem Inc., and American Piezo all supply the material in a variety of milled sizes and shapes [4]. Illich also provides calculated constants for the PZT-5A material in his LTSpice model of piezoelectric ceramics [5].

[5] Discussion of LTSpice modeling of piezoelectric ceramics is dicussed later in Results chapter

With a material chosen, a frequency region must also be chosen. Low frequency ($<$ 20Hz) was disqualified because of its low propogation through media and its low conversion efficiency in piezoelectric ceramics. Audible frequencies (20Hz to 20kHz) were disqualified because the applicability of such a system would only be in unmanned areas due to safety concerns. High frequencies ($>$ 10GHz) were also disqualified due to expense and relatively low power of amplifiers in that range. So, a range from 20kHz to 10GHz was opened. To begin, a piezoelectric was designed for a frequency of 500kHz, a frequency which allows for the use of linear amplifiers that have been developed for distress radios.

Design of the piezoelectric from a given shape, material, and frequency is then (ostensibly) deterministic. Calculation of the diameter is performed from the given correlation to resonant frequency in planar mode ($d > 5t$)

$$f_{res} = \frac{N_r}{d} \therefore d = \frac{N_r}{f_{res}}$$

where f_{res} is the resonant frequency in Hz, N_r is the radial piezoelectric coefficient given in [4], d is the diameter, and t is the thickness. An example of a disk transducer with its induced force occuring in the $\vec{3}$ direction is shown in figure 2. The calculation results in a diameter of 2.9mm and a thickness $\leq$ 0.58mm.

Two simulations were performed to check this analytical solution. The first simulation used COMSOL multiphysics simulation platform and combined the structural mechanics (stress-strain) equations and the piezoelectric constitutive equations in the frequency domain for solution of the voltage and current density of the given sized

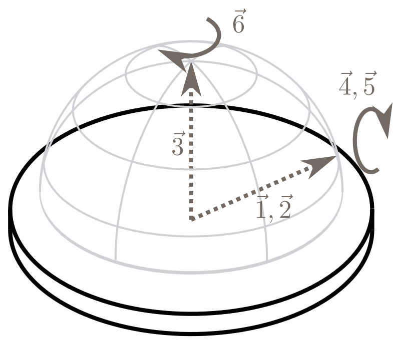


Figure 2: Coordinate system for disk pzt

transducer. A diagram of the mesh and boundary conditions are shown in figure 3. Boundary condtions are:

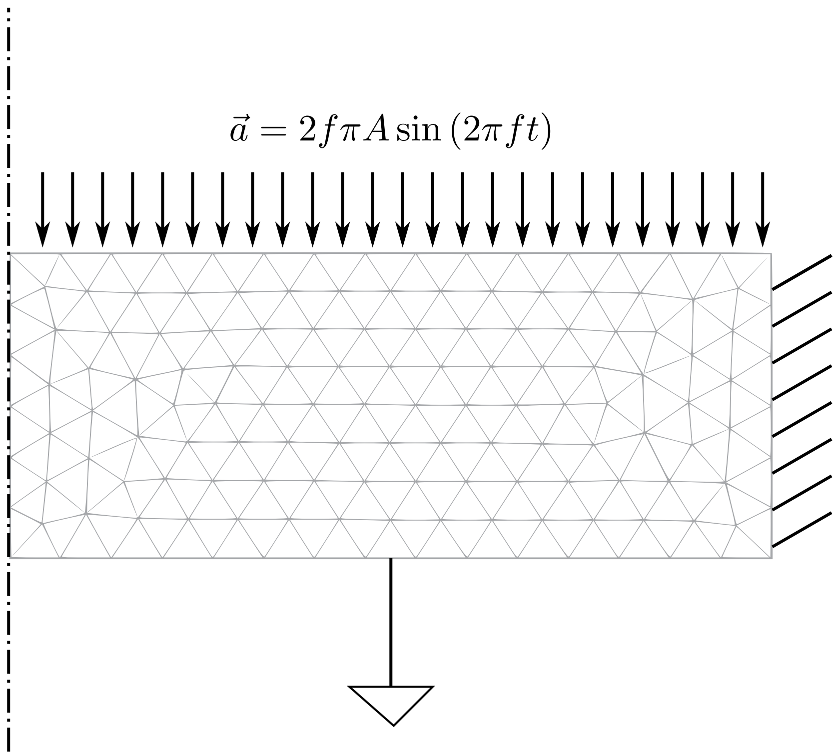


Figure 3: Mesh and boundary setup for finite element simulation of PZT-5A disk

- Bottom boundary:
  - Electrically grounded
  - Mechanically free
- Left boundary:
  - Electrically and mechanically axial symmetry (rotation around this axis in 2π)

- Right boundary:
  - Electrically floating
  - Mechanically fixed - assumption that the boundary is rigid
- Top boundary:
  - Electrically floating
  - Mechanically applied acceleration $\vec{a}$ at frequency f

Calculation of the acceleration is perfromed using a fourier transform and assumptions about the sound pressure level. A sound pressure level of 40dB, which is equivalent to a normal conversation, corresponds to a particle velocity amplitude of $1.0 \times 10^{-6} m/\mathrm{s}$. In the transient domain, this can be written as

$$\vec{v} = A \sin(2\pi f t)$$

performing a derivative on this give us

$$\vec{a} = \frac{d}{dt}\vec{v} = \frac{d}{dt}\left[A \sin(2\pi f t)\right]$$
$$\vec{a} = 2\pi f A \cos(2\pi f t)$$

and performing a fourier transform to place this into frequency space, we can get the acceleration at the boundary in frequency space as

$$\vec{a}_{\mathscr{F}} = \mathscr{F}(\vec{a}) = \frac{2\pi f A + 2\pi f A}{2i}$$

and thus, the boundary condition for COMSOL can be seen to be $\vec{a}_{\mathscr{F}} = 2\pi f \vec{v}_{\mathscr{F}}$.

A second simulation was created for the sake of PZT frequency analysis. This simulation used Linear Technology's version of the SPICE simulation package, a University of California Berkeley product for simulation of circuits. Illich provides a subcircuit which uses an analogy between current and sound particle velocity and lossy transmission lines to simulate piezoelectric material and acoustic media [8]. A frequency sweep calcualtion was performed with the applicaton of $1.0\bar{}\mathrm{A} \models 1.0 \times 10^{-6} m/\mathrm{s}$ to the piezoelectric face.

The results of these simulations were quite suprising. The voltage, current, and power are shown in figures 4, 5, and 6, respectively. While SPICE indicates a resonance in power at $\sim$ 500kHz as expected, COMSOL indicates a resonance for **admittance** of power at that frequency. Thus, it can be concluded that this resonance would not occur in a real PZT. The largest resonance in both models occurs at 1.62MHz, a harmonic of the 500kHz frequency desired. Because of the maximum power output occuring at this frequency, the rest of the analysis can be done using 1.62MHz.

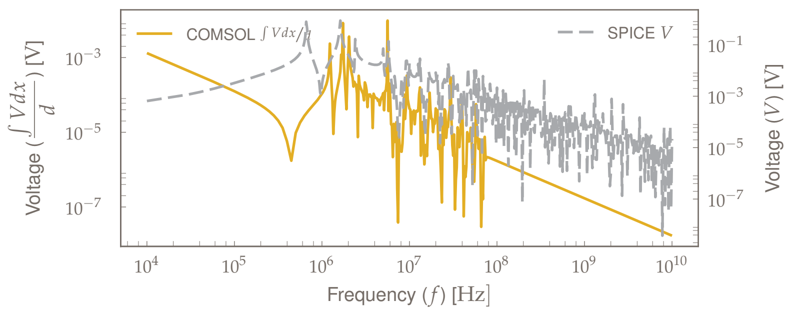


Figure 4: Across capacitor voltage versus frequency

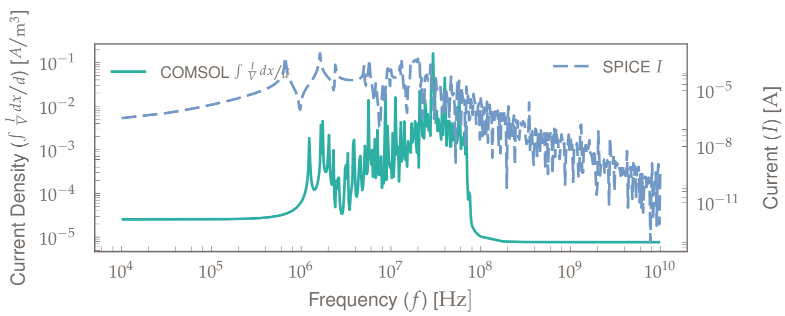


Figure 5: Current density generated in piezoelectric harvester versus frequency

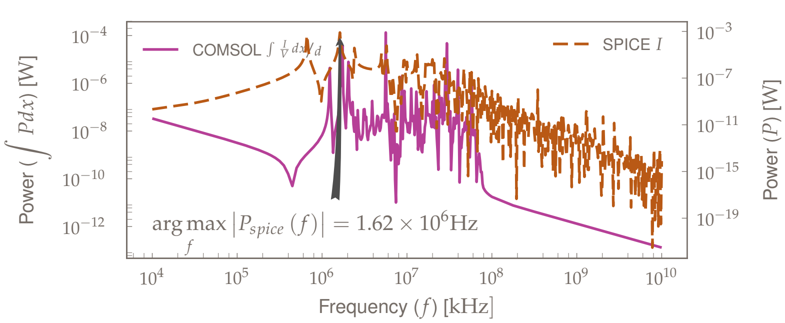


Figure 6: Power generated in PZT with frequency

Resonant Circuit Design

In order to properly admit the power generated in the PZT into a voltage regulator so that it can be supplied to real electronics, an oscilating circuit must be designed to match the frequency of the output from the PZT. An RLC circuit is then desired, as shown in figure 7. Two simplifications can be made to this circuit, the first

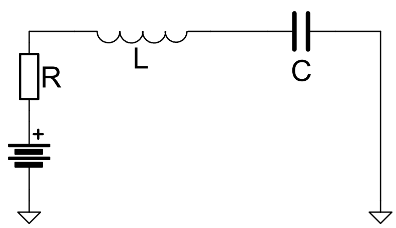


Figure 7: Diagram of series RLC circuit

removing the resistor (creating an LC circuit), the second removing the inductor (creating an RC circuit). The resonance for an LC circuit is given as

$$f_{res} = \frac{1}{2\pi\sqrt{LC}}$$

and the resonance for an RC circuit is given as

$$f_{res} = \frac{1}{2\pi RC}$$

Apparently, there are infinitely independent solutions of L and C or R and C given f_{res}. However, the smaller the product of the L and C is, the wider the Q value (or peak amplitude divided by peak width). Thus, a small C value is desired for both circuits. A capactior value of 10nF was chosen for both circuits. However, the PZT has capacitance inherent in the material. The PZT has an internal capacitance of

$$C = \frac{\pi}{4} k_{33} \varepsilon_0 \frac{d^2}{t} = 0.1\text{nF}$$

Thus, we have to ballast the PZT with a parallel capacitor of 10nF.

SPICE modeling gives results for the sweeping of L and R while keeping f_{res} and C constant. The results are given in figures 8, 9, 10, and 11. The resistance sweep shows that the R corresponding to f_{res} is actually filtering out half of the output signal (creating a lowpass filter). Thus, the lowest resistance value possible is desired. This means an LC circuit is desired. The inductance sweep shows that a voltage and current peak is maximized at the L value calculated by $f_{res} = \frac{1}{2\pi\sqrt{LC}}$, and is equivalent to 10nH.

Figure 8: Voltage at power out terminal versus time versus matching resistance

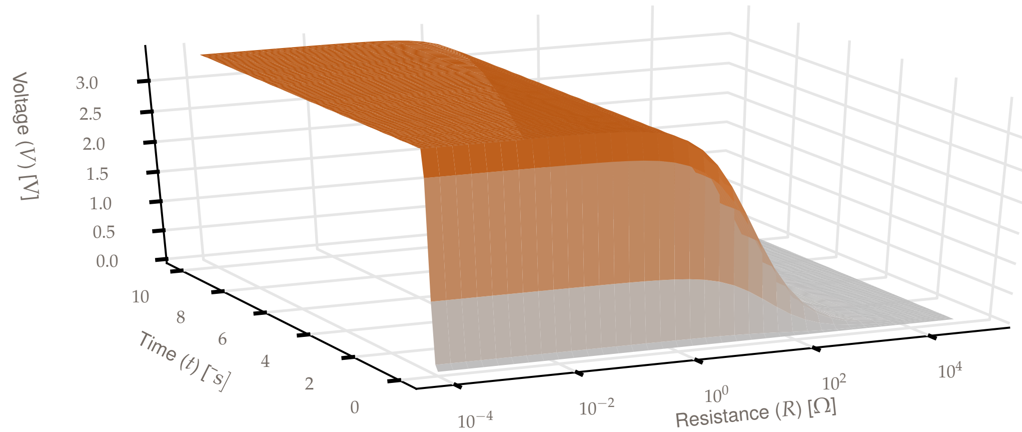
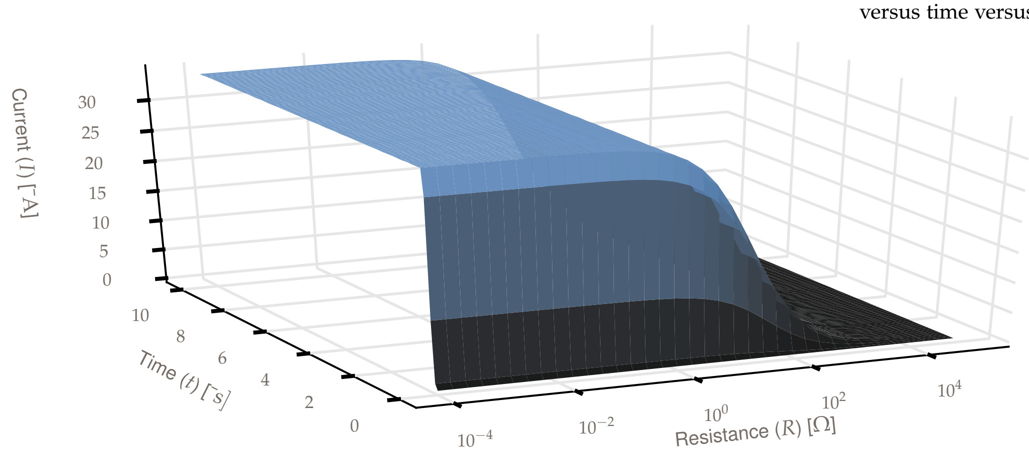


Figure 9: Current at power out terminal versus time versus matching resistance



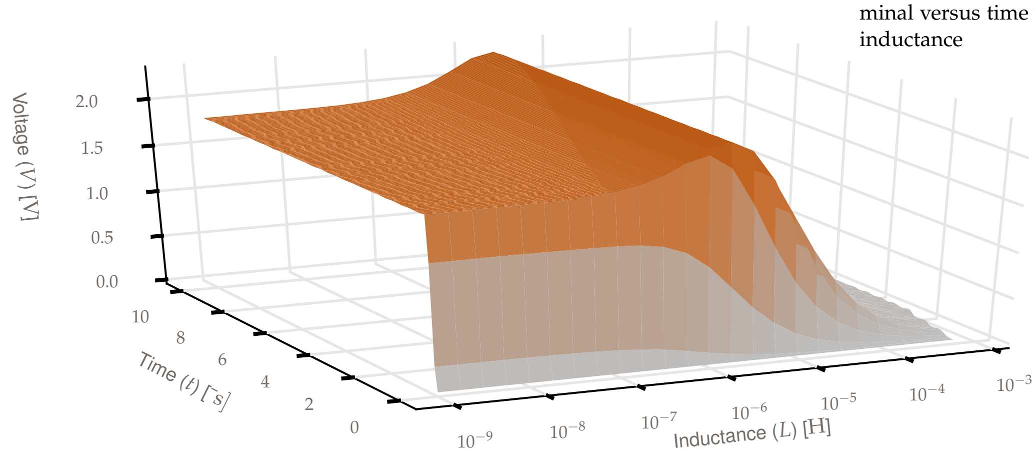


Figure 10: Voltage at power out terminal versus time versus matching inductance

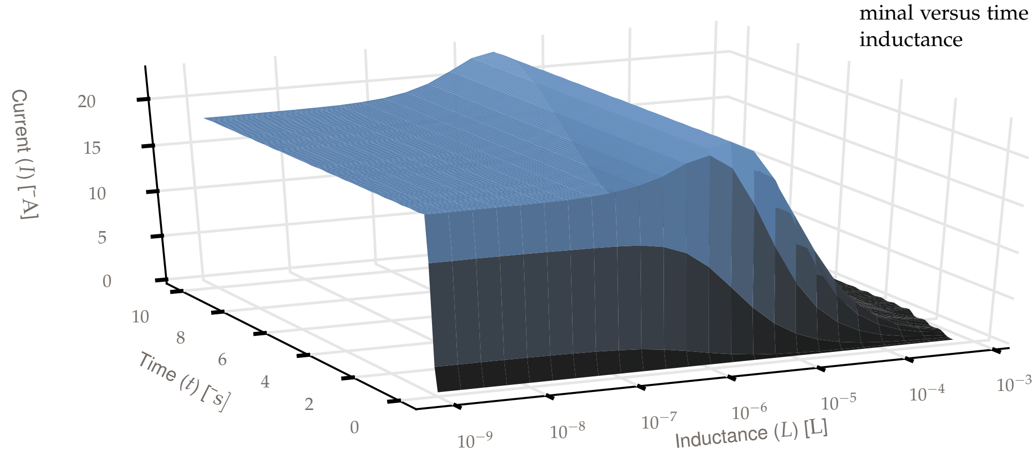


Figure 11: Current at power out terminal versus time versus matching inductance

Regulator Choice

With the resonant circuit matched to an optimized PZT geometry, now a voltage regulator must be chosen for conversion from a sin wave input of power to DC output power. Microprocessors can run on anything from 1.8V to 12V, depending on the model, but they require protection and stability in the voltage. Botteron suggests a purpose designed regulator, called TI's BQ25504 which is described as an "Ultra Low-Power Boost Converter With Battery Management for Energy Harvester Applications" [23]. An example system design using this boost converter is shown in figure 12. In order to realize

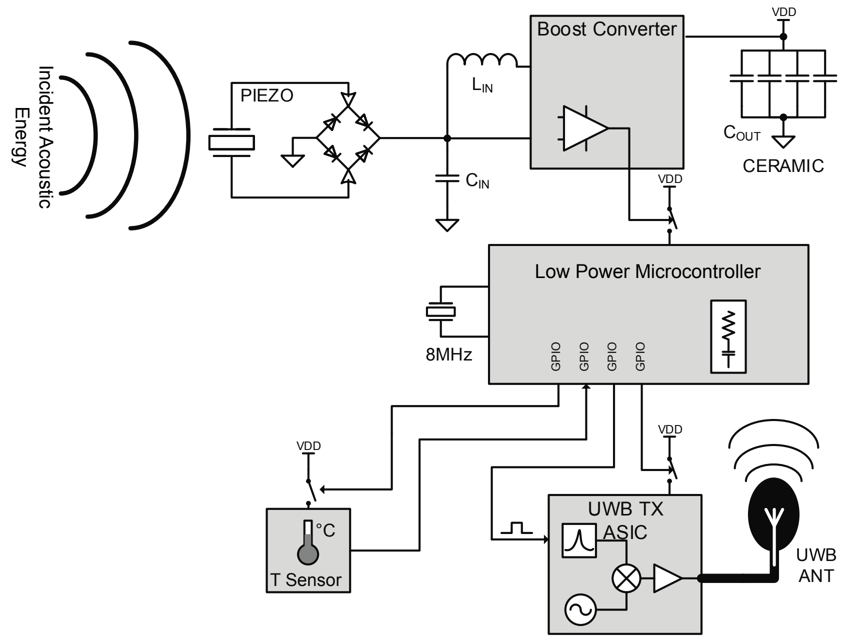


Figure 12: System design with inspiration from [2] before iteration

this model, a schematic circuit was designed using the BQ25504 and suggested fixturing [23]. This circuit is shown in figure 13. Tests using spice simulation and the circuit with the BQ25504 resulted in incredibly low performance. Maximum voltage was $\leq$ ¯V, and maximum current was $\leq$ nA. This did not reach the stated goal of 37¯W, and thus other designs were required.

TI describes the BQ25504 as a **boost** converter, which actually converted current to voltage to provide an output voltage higher than input voltages, with input voltages down to 0.2V. After inspection, it was seen that the PZT actually supplies high voltage and low current, with some voltages oscilating from 10*s* of amperes positive and negative. Thus, a step-down converter was actually needed. A voltage regulator that fit this requirement was chosen from Linear Technologies. The LT1587 is built for supplying high current regulated voltage

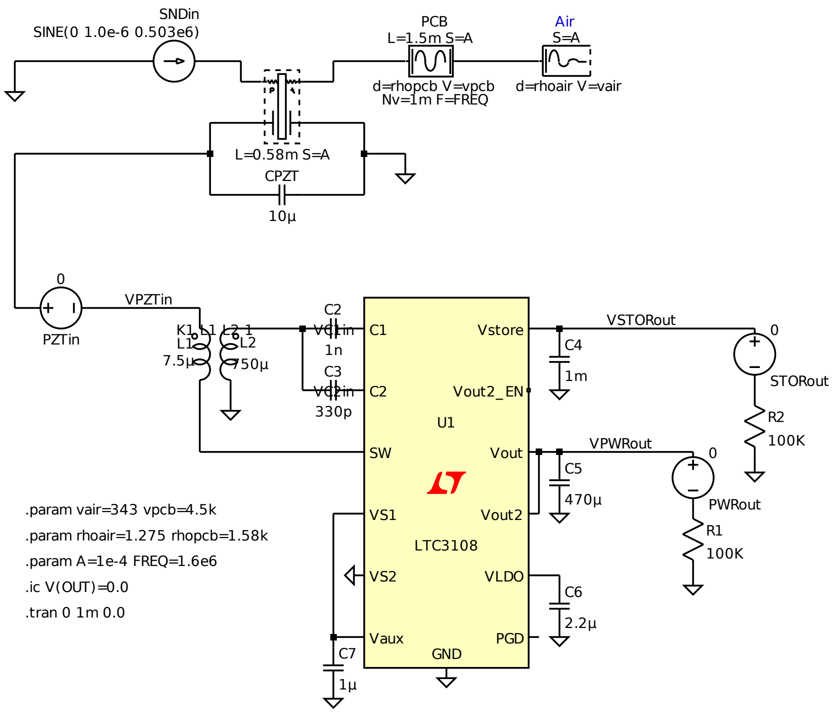


Figure 13: Circuit diagram for circuit iteration using transformer and LT3108

with low dropout and at high frequency [13]. This is perfect for the piezoelectric application. The design for this system is shown in figure 14, using either an LC or an RC circuit as indicated by the dashed lines through the inductor and resistor.

To analyze the circuit described in figure 15, first a small frequency sweep was performed to ensure that the system oscillated at the design frequency. The sweep was performed in the region around 500kHz to 2MHz, and the voltage and current results are shown in figures 15 and 16. It can be seen that the maximum current and voltage output does occur at around 1.6MHz. With this verification, the performance of the circuit could then be evaluated.

A transient analysis of the circuit was then constructed. The transient analysis was performed with an LC and an RC circuit, but as shown previously in the analysis, it is obvious that the RC circuit will perform 1/2 as well due to the filtering effect. The analysis was performed for 4¯s, during which time steady state was reached. Figures 17, 18, and 19 show the response of the circuit over that time period from initial conditions of $V_{out} = 0V$ and $I_{out} = 0A$. The results are quite encouraging, with the power output coming to 125¯W steady state, delivered at 3.6V.

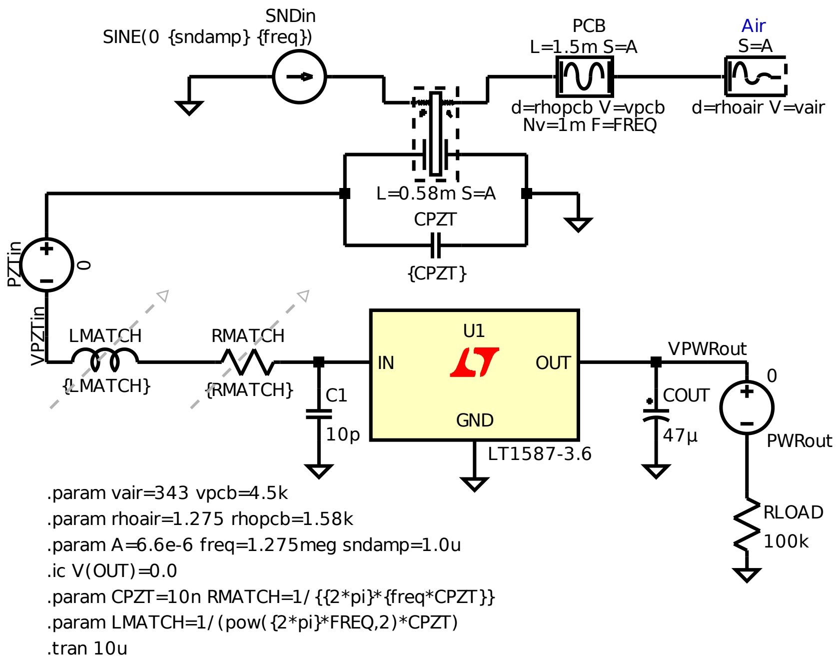
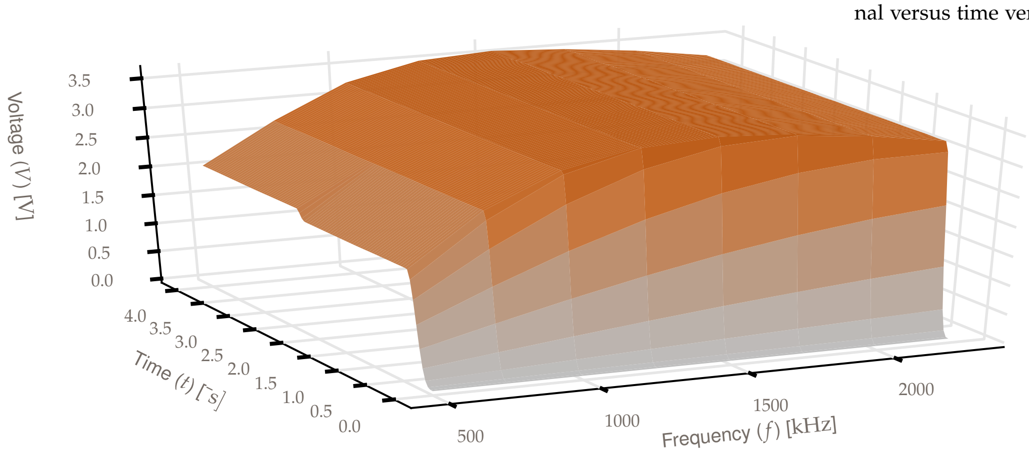


Figure 14: Circuit diagram for circuit iteration using LRC oscilating circuit and LT1587-3.3

Figure 15: Voltage at power out terminal versus time versus frequency



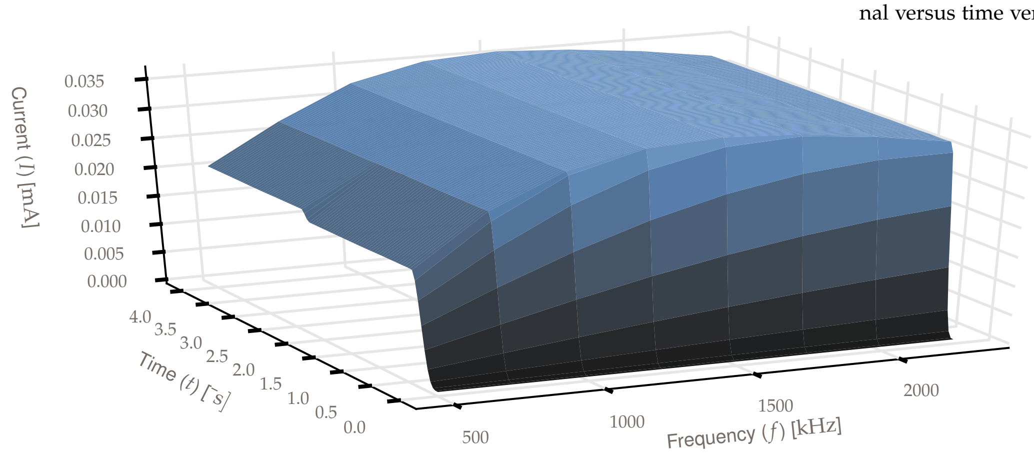


Figure 16: Current at power out terminal versus time versus frequency

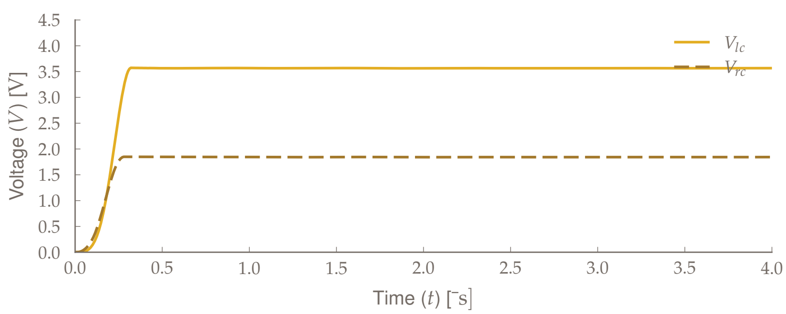


Figure 17: Voltage at power out terminal versus time

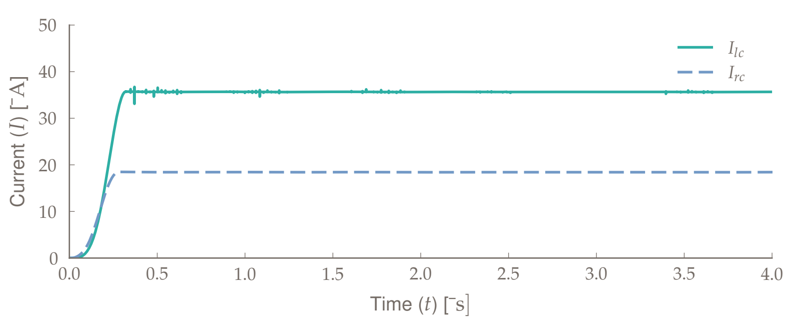


Figure 18: Current at power out terminal versus time

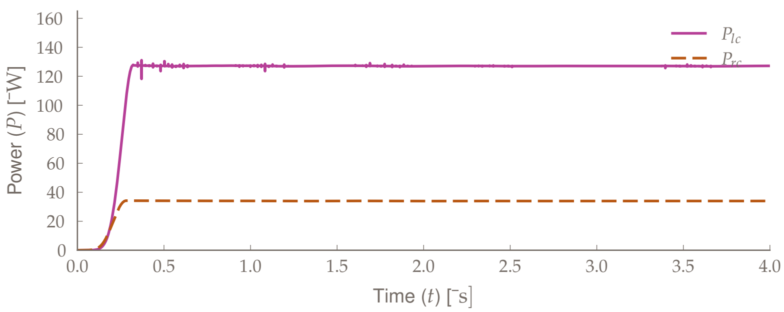


Figure 19: Power at power out terminal versus time

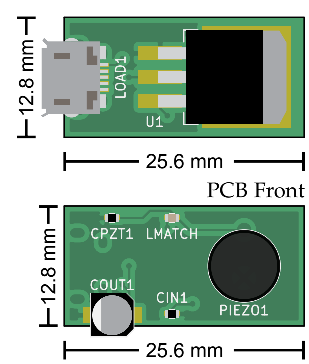
Discussion

The final iteration of the design proposed includes only the design part of the stated goals. The comparison to other technologies ended up being beyond the scope of this writeup. The goals stated for the energy harvester are reproduced below

- Develop an active piezoelectric power system to take measurements and transmit them via ultra wideband radio, as in [2].
  - Match or increase requirement for 12.6 μW for one readout every 34s
  - Decrease size because of removed requirement of solar cell and cantileiver type piezeoelectric harvester (less than $85 \times 25\text{mm}^2$)
  - Determine if same structure can be used to take readout of separate piezoelectric vibration sensor

The three goals stated were met and exceeded by the design. The power output from the goal to the final design was increased tenfold, from 12.6¯W to 125¯W, while the size of the circuit was decreased. The final size of the circuit is 25mm $\times$ 12mm as shown in figure 20, but the piezoelectric itself has a surface area of only 6.6mm^2.

Most of the size comes in the electrical connection and the voltage regulator. The design requires only a 40dB input sound, at 1.6MHz, which could is inaudible and could be present in most spaces without undue health hazards to occupants. The rise time of the circuit is $\ll$ 4¯s, and the output voltage is 3.6V, which makes it a drop in replacement for a single cell LiPo battery.



PCB Front

PCB Back

Figure 20: PCB Design exported after generating netlist and schematic

The Future

There are many recommendations for extension on the current design. The first recommendation would be to use electronic design software to create a printed circuit board for one of these transducers and test the performance of a real system. This would inform to other structural resonances and electrical characteristics (such as line resistance or impedance) that may be important. Also, full optimization of the PZT material used (perhaps polyvinylidene difluoride) could provide better results due to higher voltages. Along with different PZT materials could be different frequency regimes. For WiFi amplifiers, instead of radio, frequencies in the GHz range could be easily amplified and supplied into a system. If the system were designed at these higher freqencies, it may be more about to generate higher power, but requires full design from the PZT size and shape. Finally, the integrated circuit step down converter should be optimized, as the efficiency of conversion from high voltage into current was not a focus when choosing the voltage regulator, and may not be optimal.

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