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A New Technique to Control Wireless Underwater Power Transmission

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ABSTRACT: **Wireless Underwater Power Transmission (WUPT) is an affordable device designed to provide power to submerged systems and devices. The system consists of a transmitter, receiver, charging circuit, and rechargeable battery. The objective of WUPT is to provide a device capable of transmitting power wirelessly underwater and storing the power provided in a battery. The primary motivations for the device are to provide a cost effective alternative to powering submerged devices as well as offering a method for increasing the sustainability and lifetime of existing devices. The ultimate goal is to be able to transmit power with efficiency greater than or equal to 10% to charge a 3.7 V Lithium-ion battery.**

Index Terms- **function generator, charging circuit, li-ion battery, oscilloscope**

1. Introduction

Wireless Underwater Power Transmission (WUPT) is an affordable device designed to provide power to submerged systems and devices. The system consists of a transmitter, receiver, charging circuit, and rechargeable battery. The team requests $400.00 to fund the prototype of the WUPT device. The material that will be used is Lead Zirconate Titanate (PZT-5H, DoD Navy Class VI) piezoelectric with a resonant frequency of 2.2 MHz due to the high sensitivity. The core component of the transmitting and receiving system consists of eight piezoelectric transducers. A function generator is used to supply a 2.2 MHz square wave potential to four of the piezoelectric transducers on the transmitting end. On the receiving end, the remaining four transducers convert the incoming acoustic signal to an electrical signal, inducing a current into the charge pump. The battery charging configuration consists of five stages: charge pump, trickle charge, constant current, constant voltage, and end of charge detection. The charging circuit Can be either designed using a digital microcontroller or analog domain system, the digital configuration is advantageous because it provides precision (<1% of target) and will take half the amount of time. The team requests $400.00 to fund the prototype of the WUPT device

2. Objective

The objective of WUPT is to provide a device capable of transmitting power wirelessly underwater and storing the power provided in a battery. Figure 1 presents a block diagram of the WUPT system. An electrical signal is inputted into the transmitter side of the system where it is converted to an acoustic wave and sent to the receiver. The receiver reverses the conversion process, producing an electrical signal that is routed through a charging circuit responsible for regulating current to the rechargeable battery and detecting when it is fully charged. The battery is responsible for providing an energy source to a connected device

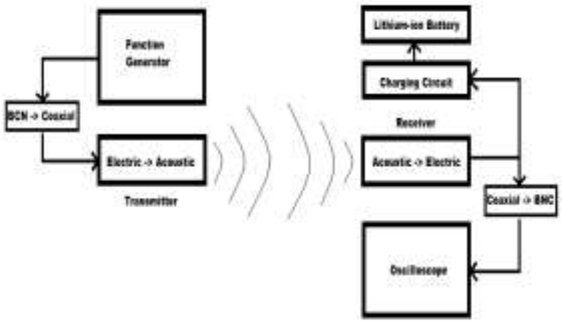

Fig. 1 General block diagram

2.1 Motivation

The primary motivations for the device are to provide a cost effective alternative to powering submerged devices as well as offering a method for increasing the sustainability and lifetime of existing devices. Applications where underwater power transfer could enhance performance capabilities include power deliver to oilrigs, deep-sea submersibles, and mining operations. Particularly in the oil industry, devices are dropped into deep-sea environments to sense oil deposits under the ocean floor and send data back to a received on the surface. These devices tend to have poor battery life and are frequently replaced because the amount of energy stored is their limiting factor. WUPT provides a method of powering these devices, reducing the cost to companies for replacing them and increasing their reliability and sustainability

2.2 Background

Current methods to underwater power transmission include fully tethered systems where long cables are connected to directly deliver power, mobile submersibles making frequent trips to submerged systems, and systems that harvest energy using aquatic wave motion. These methods become unreliable in deep-sea environments due to the pressure change combined with the increased transmission distance. Furthermore, ocean current towards the ocean floor is negligible for harvesting energy. Extensive research has been devoted to wireless power transmission systems; however limited research involves systems in submerged environments. Piezoelectric transducers (PZT) have become the primary component involved in accomplishing this task. These transducers make use of the piezoelectric effect, a process generating an electrical charge from an applied mechanical force. Being a reversible process, an applied electric signal applied to a piezoelectric material can produce an internal mechanical strain. The piezoelectric effect is caused by electric dipole moments in solids resulting in momentary deformation, a process known as electrostriction. The periodicity of this deformation causes the material to vibrate, generating plane waves. Likewise, deformations caused by pressure cause dipole moments resulting in a current flow to generate an electric signal. PZTs have uses in various applications in addition to power transmission. Common applications include sonar receivers, electronic frequency generation, and hydrophones.

3. Seminar Description and Goals

The objective of WUPT is to charge an underwater battery by converting an electrical signal to an acoustic signal, transferring that signal through the water medium, then interpreting that signal to charge a Lithium-ion battery. The system can be divided into three portions: transmitting, receiving, and the charging stages. The core components of the transmitting and receiving system consist of eight piezoelectric transducers soldered to coax cables.

A function generator is used to supply a potential to four of the piezoelectric transducers on the transmitting end which will produce the acoustic signal. On the receiving end, the remaining four piezoelectric convert the incoming signal to an electrical potential, inducing a current, supplying a charge pump. The charge pump will amplify the voltage to the charging circuit, and as a result charging the battery. The seminar goals are as follow:

a) converting an electrical signal to an acoustic signal

b) Transmission of power

c) Conversion of an acoustic signal to an electrical signal

4 . Technical Specification

Here, Table1 shows the technical specification for wireless underwater power transmission system. Technical specification includes numerical values of features added in system. Here piezoelectric transducers work on the these specifications

Features	Specifications
Operating Frequency	2.2 MHz
Propagation for Power Transmission	166 m/s
Input Power Supply	20 V
Maximum Distance to Transmit	18-24 inches
Epoxy thickness	20 μ_m
Charge Pump	
Efficiency of Power Received to Total Power Transmitted	10 %
Coaxial Cable length	$\lambda/2$
Temperature of water (DI)	20 °C
Lithium-ion Battery	3.7 V

5. Design Approach and Details

5.1 Design and Details

In designing up of wireless underwater power transmission, a detailed design approach, power transmission, battery recharging and etc are explained as below.

5.1.1 System Overview

The Underwater Power Transfer System will consist of a power transmitter, a power receiver, a charging circuit, and a Lithium-ion battery. The power receiving unit will be submerged in water and is responsible for converting the acoustic signal to an electrical signal, thus charging the battery.

Piezoelectric transducers are responsible for the power transmission as well as the receiving power. A function generator will be connected to the emitting transducer. The piezoelectric crystal will then convert that electrical signal to an acoustical signal. Once that acoustical wave propagates through the water medium, a piezoelectric receiving transducer will be in place to convert the acoustic signal to an electrical signal. The induced voltage is then applied to the charging circuit which charges the Lithium-ion battery. The system will be completed in two phases: Power transfer and Battery Charging.

5.1.2 Power Transmission

The ultimate goal of the power transmission phase is to convert an electrical signal to an acoustic signal then have the signal propagate through water. The configuration for the transmitting and receiving transducer are identical. Figure 2 shows a prototype model of the transmitting configuration.

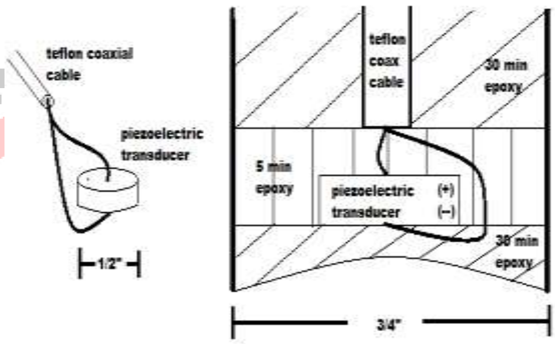

Fig 2
Prototype model of transmitting/receiving transducer with PZT-5T piezoelectric

The material that will be used is Lead Zirconate Titanate (PZT-5H, DoD Navy Class VI) piezoelectric. This material was chosen due to the high sensitivity of the piezoelectric. The two circular surfaces act as the positive and negative electrodes for the piezoelectric. A Teflon-coated coaxial cable (RG-178) is used to transmit the signal from the function generator by soldering to the piezoelectric. The properties of coaxial cable introduce very low noise into the signal and the Teflon is impermeable to water. Four piezoelectric transducers in an array will be situated inside of a plastic casing, oriented with their respective flat surfaces in the direction of wave propagation. Epoxy will be used to insulate the electrodes as well as providing a quarter-wavelength impedance matching layer on the front surface of the transducer. To determine the thickness of the quarter-wavelength layer, Table 2 shows parameters of the water medium.

Table 2
Table of Parameter for medium of Water

Resonance Frequency (f)	2.2 MHz
Speed of Sound in Water (c_0)	1484 m/s (20° C)
Relative Permittivity of Water (ε_r)	80 (F/m)
Relative Permeability of Water (μ_r)	1 (H/m)
Permittivity Permeability of Free Space (ε_0, μ_0)	8.854×10-12F/m, 4π×10-7H/m
Conductivity (σ)	10-3 (S/m)

From Table 2, the period can be found by taking the inverse of the resonance frequency. As shown in Equation 1, a period of 0.455 µs is found, given our resonance frequency.

$T=1/f$ ……………………….(1)

Due to the propagation losses that occur when transmitting in water, the phase velocity is the speed at which the wave propagates, given a specific frequency. The phase velocity is determined below by Equation 2.

$vp = c0/\mathrm{sqrt}(\mu r \varepsilon r)$ ……………..(2)

The phase velocity is found to be approximately 166 m/s propagating through water. The wavelength of the propagating signal should be found for two reasons: To find the thickness of the epoxy layer that should be put in place and to find the electrical length1. The wavelength and electrical length are given by Equations (3,4), respectively.

$\lambda = vpT$ ……………………..(3)

$EL = l/\lambda$………………….. (4)

With a resonance frequency of 2.2 MHz, the wavelength is 75.4 µm, resulting in an electrical length of 7400. In order to impedance match the water and transmit maximum power at the resonance frequency, the thickness of the epoxy layer should be approximately 20 µm. Two different grades of epoxies are used in the transducer construction. A fast-action epoxy is used behind the piezoelectric with a dry-time of approximately 5 min. simply to insulate the wires and to hold the transducer in place. Proceeding, a 30min. dry-time epoxy is used to couple the boundary of the water medium on the front and back of the transducer, with the coaxial cable held in place.

5.1.2 Signal Propagation

The ultimate goal is to be able to transmit power with efficiency greater than or equal to 10 %. For this reason, a 2.2 MHz square-wave operated in burst-mode will be sent through the function generator. The square-wave is chosen because the root-mean square (RMS) of a square wave is the amplitude (A). Burst-mode is chosen because the most mechanical vibrations will occur from constant pulses, rather than a continuous signal.

The power transmitted through the medium of water can be modeled by an equation as a function of distance. The attenuation is a gradual loss of power transmitted as distance increases, shown in Equation 5

$\alpha = \mathrm{sqrt}(\pi\mu\sigma f)$…………………(5)

The attenuation constant for fresh water at 20° C is 0.0932 Np/m. The intrinsic impedance of the water medium is found to be 131.8 ∠ 45° Ω by substituting Equation 5 into Equation 6, where σ represents conductivity in the water medium.

$\eta=(1+j)\alpha/\sigma$ ………………(6)

The power transmitted (S) at any single dimensional distance from the transmitter can be modeled by the function shown in Equation 7, where Ex0 is the electric field constant and z is distance from the emitting transducer. Equation 7 will be the foundation of what distance to place the receiving transmitter, at the transmitting resonant frequency, to receive maximum power. Figure 3 shows there is an exponential decrease in power transmitted as a function of distance from the emitting transducer. Equation 7 and Figure 3 show that for maximum power transmission, the receiving transducer should be placed exactly 0.559 m from the emitting transducer (transition from near field to far field).

$S(x) = |Ex0|2/(2|\eta|)e2\alpha x\cos(<\eta)$…………(7)

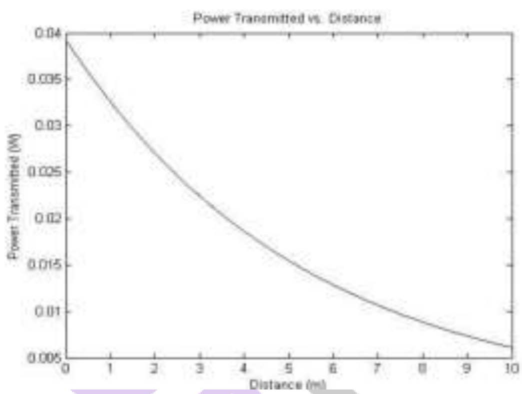

Fig 3 power transmitted as a function of distance from the power emitting transducer

5.1.4 Battery Charging

The receiving transducer converts the acoustic signal to an electrical signal and has the same configuration as the emitting transducer. The battery charging configuration consists of five stages: charge pump, trickle charge, constant current, constant voltage, and end of charge detection. This setup, as shown in Figure 4, can be arranged in both the analog and digital domain, but will depend on how much power is received compared to the respective require Figure 4

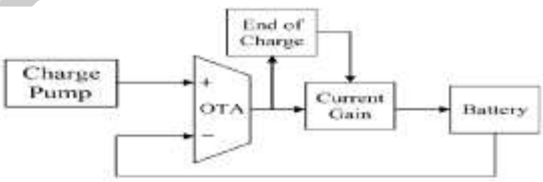

Fig 4 Block diagram represents Lithium-ion battery charging configuration

The charging state is bounded by constraints of the Lithium-ion battery as shown in Figure 5. During trickle charge, the battery is charged with a small amount of current, typically no more than 0.1 times the rated capacity expressed in terms of Ah, or C. Charging currents greater than 0.1 C may be hazardous since the battery has high internal impedance at these low voltages and is susceptible to thermal runaway. Above the rated threshold of the battery, the battery may be charged at higher currents, typically less than 1 C; this charging profile section represents the constant-current region. As the battery voltage approaches its maximum respective capacity, the charging profile enters the constant-voltage region. In this region, the charging current should be progressively decreased as the battery voltage approaches its respective maximum. Charging current should be decreased until a certain threshold is met, typically about 2% of the rated battery capacity. Once this charging current is reached, the charger enters the end-of-charge region

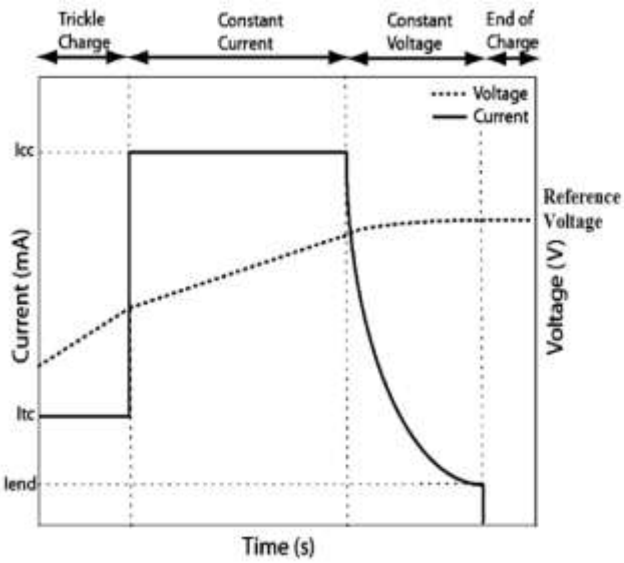

Fig 5 Charging profile for a Lithium-ion battery

5.2 Codes and Standards

1. Secondary lithium battery safety precautions to ensure their safe operation under intended use and reasonably foreseeable misuse .
a) not to exceed maximum voltage capacity of battery

b) not to drain battery voltage lower then specified voltage

c) Harmonization with IEC 62281.

1. Piezoelectric transducer (PZT-5H DoD Navy Class VI) is an electromechanical crystal which can induce a pressure or voltage. It features:
   a) A compliance of 10-12 m2/N
   b) A piezoelectric coupling of 10-12 C/N

5.3 Constraints, Alternatives, and Tradeoffs

5.3.1 Constraints

The power transmission efficiency of the underwater power transfer system is constrained by factors such as:

a) Size/phase change of the transducers

b) Soldering joints to the piezoelectrics

c) Water tank used for testing

d) Variations in the water medium

e) Impedance matching between different stages

1.Size/Phase Change of Transducers
The transducer size is directly proportional to the amount of power that can be transferred. Since ½ inch piezoelectrics will be used, four or more of them must be used in parallel to receive 5 V at the charging circuit. There will be a slight phase difference between each of the piezoelectric which will limit the transmitting power

1. Soldering joints to the piezoelectric
The initial soldering procedure applies a high temperature on the piezoelectric which will taint the crystal. The affected region on the crystal will have degenerative characteristics in comparison to the complete piezoelectric, consequently, lowering the efficiency

3. Water tank
The water tank that will be used is bounded by glass walls which will cause multipath reflections from the emission signal. These reflections will be out of phase from the transmission signal and lower the transfer efficiency.

4. Variations in the water medium
Water is a deformable body, constantly in motion. The variation in the medium will constantly alter the signal propagation as well as the intrinsic impedance of the water, consequently limiting the transmission efficiency

5. Impedance matching between different stages
The proposed design contains eight stages, each of which will have a different amount of power reflected. The error of impedance matching each stage will subsequently result in the major constraint of the design.

5.3.2 Alternatives

The charging circuit can either be designed using a digital microcontroller or in the analog domain using the hyperbolic tangent (tanh) basis. In the analog domain, the efficiency is much greater (89.7%) due to CMOS technology, is cost efficient, will consume less power, but will take much more time and yield more possibility of error. The digital configuration is advantageous because it provides precision (<1% of target) and is time efficient, but will consume more power and costs five times as much.

5.3.3 Tradeoffs

Using commercial grade electrical-to-pressure transducers instead of fabricating transducers from piezoelectric will increase the effective range as well as the transmission power. The disadvantage is the cost of commercial transducers (75% higher costs). The tradeoff is sacrificing transmission power and effective range to avert costs, or vice versa.

6. Seminar Demonstration

The transmitter and the receiver will both be placed in a tank of distilled water at 20° C, facing each other, as shown in Figure 6. The transmitter will be connected to a function generator and the receiver will be connected to an oscilloscope for measurement purposes.

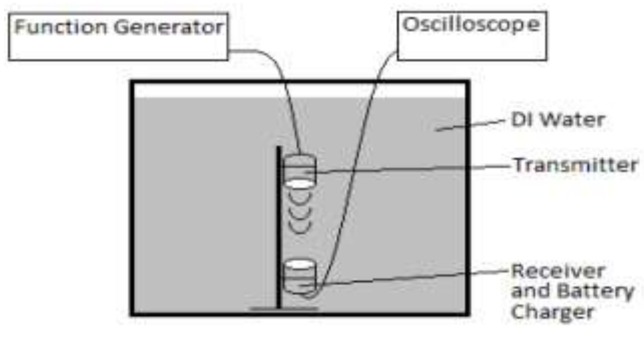

Fig 6 Demonstration setup for WUPT system

Before the demonstration begins, the charge of the lithium-ion battery will be recorded. To begin the demonstration, the function generator will be set to produce a square wave, operating in burst mode, with a frequency of 2.2 MHz. Immediately after the function generator is turned on, the receiver will begin providing power to the battery charging circuit. The oscilloscope will show the voltage that is produced at the terminals of the Li-ion battery. This reading will also show the overall power loss from the function generator to the battery. The system will run until adequate data is obtained, after which the function generator will be turned off, and the battery's charge will be recorded again, and compared to its original charge.

7. Conclusion

Wireless Underwater Power Transmission technology is a non-radioactive mode of energy transfer, relying instead on the magnetic near field. Magnetic fields interact very weakly with aquatic organisms and animals—and are scientifically regarded to be safe. WUPT products are being designed to comply with applicable safety standards and regulations. Hence WUPT is technology can transfer power depends on the source and receivers. if it is relatively close to one another,and can exceed 95%.Efficiency,Efficiency is primarily determined by the distance between the power source and capture device, however. Traditional magnetic induction requires that the power source and capture device be very close to one another usually within meters to transfer power efficiently. Wireless Underwater Power Tranmission technology is based on sharply resonant strong coupling, and is able to transfer power efficiently even when the distances between the power source and capture device are several times the size of the devices themselves.

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