Experimental Testbed for Ultrasonic Wireless Power Transfer and Backscattering Based Localization for Future Implantable Devices

Collin Kummer, Joseph Summers, Quinton Lum, Carl Sundsten, Chung-Ching Lin, Subhanshu Gupta
Washington State University
Pullman, United States
Collin.Kummer@wsu.edu

Stephen Seslar, Wayne Monsky
Pyrus Medical Inc.
Seattle, United States
Steve@pyrusmedical.com, Wayne@pyrusmedical.com

***Abstract*— The development of an autonomous tracking system which could accurately locate and transfer higher quantities of power wirelessly to deep-tissue catheter implants in a cost-effective manner would prove very useful in medicine. This work presents a backscatter-based energy transfer and tracking system for future deep-tissue implants. To transfer power, an open-top ultrasonic transducer would be placed near the skin, the ultrasonic wave can power circuits on the tip of the catheter inside the patient. For the tracking system, transducers use ultrasonic backscattering and time-of-arrival to precisely locate the tip of the catheter. To show this concept will work in future applications, the two major components of the system were tested and validated using commercial off-the-shelf devices with air as medium. We were able to show a one-way 0.34mm localization resolution and track an object in two dimensions with 6.32mm accuracy on the x-axis and 4.27mm on the y-axis. Ultrasonic Wireless Power Transfer (WPT) was modeled using a linear rectangular array approximation via an open-source MATLAB Toolbox known as k-Wave. The developed array model was experimentally validated at distances from 11mm to 310mm using a linear rectangular array approximation of commercially available transducers for transfer efficiencies through air of up to 81.9 percent.**

Keywords—Ultrasound, Localization, Power Transfer, Modeling, Backscattering

I. INTRODUCTION

State of the art in modern angiographic (X-ray) and non-angiographic (electromagnetic [EM] or impedance based [IMP]) catheter tracking systems cost in excess of $5M with a limited lifespan (< 5 years). In addition, they are less portable and require highly specialized operators due to the 2D gray-scale visualization used for navigation. EM or IMP navigation systems further suffer from limited tracking range and require hardwired instrumentation to be effective. The goal of the system proposed in this work is to eliminate the high cost, low practicality, and low portability that most modern systems exhibit currently using ultrasound-based wireless power transfer and tracking system. Fig. 1 shows a suggested method for devices placed at the catheter tip with the energy harvester for WPT and the external transducer for localization using the echo pulse. The devices on the catheter tip can also use harvested power from the ultrasonic WPT system and relay any sense information back to the operator.

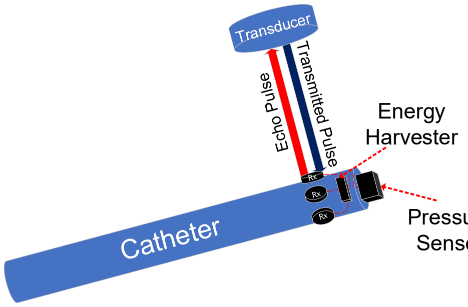

Fig. 1. Concept of a future catheter with implantable autonomous tracking system.

This work presents a proof-of-concept testbed that integrates ultrasonic-based WPT with 2D object localization with the intent of tracking and powering a deep-tissue catheter as it moves through the body (Fig. 1). Though prior works have independently researched and designed both systems [1][2], there are few designs incorporating both of them. Rapid prototyping using readily available commercial products is further adopted for proof-of-concept.

Ultrasonic WPT is adopted in this work in contrast to far-field RF WPT or capacitive WPT [3][4] because it can provide two orders of magnitude greater power using federally permitted 720mW/cm^2 limit to transmit energy [5]. In addition, it has significantly lower attenuation as it propagates across the human tissue and is thus proving to be a viable option for future implantable devices [6] that can deliver up to 1mW power reliably. Other techniques such as near-field inductive and resonant coupling WPT are size-restrictive for catheter-type applications (diameter of few millimeters only) especially at smaller microwave frequencies [7].

To achieve localization, backscattering has been shown to be a reliable and effective method for short-distance applications [8] and allows us to minimize the future implanted device size, design complexity, and power consumption by not including an active transmitter on the device. Backscattering produces one-way distances that are used in a time-of-arrival (TOA) localization algorithm, which was chosen due to its computation simplicity, ease of implementation, and its effective use in many applications [9]. The proposed testbed

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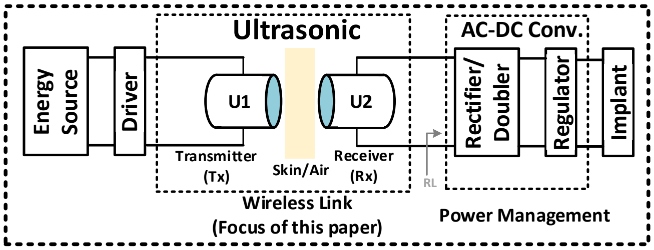


Fig. 2. System block diagram of ultrasonic based WPT.

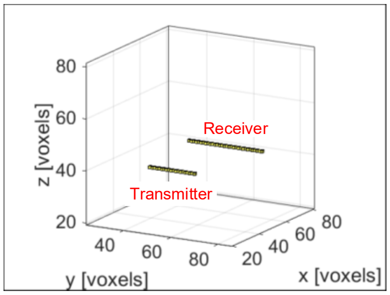


Fig. 3. Voxel plot of receiver and transmitter via linear rectangular array approximation in k-Wave simulation.

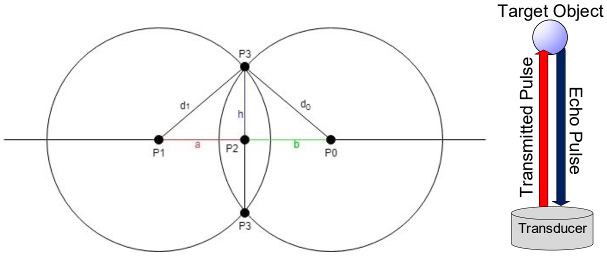


Fig. 4. Basic concept of time-of-arrival (TOA) based localization for backscattering-based ultrasonic tracking system.

demonstrates preliminary work as a proof-of-concept for future applications that could potentially make use of more complex and higher-dimensional area-mapping tracking algorithms [10].

Section II models the ultrasound-based WPT and localization technique using *k*-space pseudospectral method. Section III applies the developed model to an experimental testbed. Section IV presents the comparison of the model with the experimental results. Finally, Section V discusses the conclusions and future works.

II. SYSTEM CONCEPT FOR TESTBED DESIGN

A. Modeling ultrasound-based WPT using k-Wave toolbox

The proposed WPT system consists of a fixed open-top ultrasonic transducer placed in close enough proximity to the skin to minimize attenuation of the ultrasonic wave as it travels through the air before contacting the skin tissue. The wave will power a circuit on a catheter, which will power devices that will send vital information back to the operators such as rate of blood flow and temperature. For this proof-of-concept, two transducers are placed at distances greater than 10mm apart, facing each other, with a power harvesting circuit board connected to the system output. By having the transducers separated initially only by air, it allows for any future medium to be placed in between the transducers, showing the effects of power transfer in a different medium system.

A rough estimation of wave propagation can be obtained by using the attenuation equation below:

$$A = A_0 e^{(-\alpha z)} \tag{1}$$

where A_0 is the initial amplitude of the propagating wave, z is the distance of propagation, and α is the attenuation coefficient of the transmission material given in nepers per length. Note that equation (1) only accounts for the attenuation a single medium that the ultrasonic wave is traveling through. To effectively model reflections and account for environmental factors investigations into ultrasonic power transfer and wave propagation, calculations should be based on the Westervelt equation [11]. However, the Westervelt equation does not provide a comprehensive understanding of sound wave propagation in multiple directions. Recent developments in the *k*-space pseudospectral method had resulted in an open-source MATLAB Toolbox known as *k*-Wave Acoustics [12]. The *k*-Wave's governing equations include a generalized form of the Westervelt equation and are calculated by the *k*-space pseudospectral method using the following equations:

$$\frac{\partial u}{\partial t} = \frac{-1}{\rho_0} \nabla p + S_f \tag{2}$$

$$\frac{\partial u}{\partial t} = \frac{-1}{\rho_0} \nabla p + S_f \tag{3}$$

$$p = c_0^2 \rho \tag{4}$$

where equation (2) is the momentum conservation, (3) is the mass conservation, and (4) is the pressure-density relation.

Modeling via *k*-Wave toolbox in MATLAB was done to verify the viability of the proposed solution. The simulation environment was set up in the medium of air with a muRata MA40S4S as the transmitting transducer with a diameter of 10mm and the receiving transducer as a Kobitone 255-400SR16-ROX with a diameter of 16mm. In the simulation, the speed of sound was set to 343m/s, the density at 1.2754kg×m^{-3} at STP conditions and the alpha coefficient of air at 7.5dB/cmMHz^{y} where y is the power coefficient of 1.05. A rectangular linear array with its length equal to the diameter of the transducer is used to approximate each disc transducer. A voxel visualization of the simulation environment is shown in Fig. 3. Experimental verification of this modeling method is provided in Section III.

B. Design of Backscattering-based 2D TOA Localization System Using Two Transducers

$$x_3 = x_2 + \frac{h(y_1 - y_0)}{d}, \qquad y_3 = y_2 + \frac{h(x_1 - x_0)}{d} \tag{5}$$

Fig. 4 shows the setup for distance estimation using ultrasound-based backscattering. In our design, two transducers acting as both transmitter (TX) and receiver (RX) each engage in a burst/listen cycle that determines the one-way distance of the object from the transducer. These one-way distances each produce a circle of possible locations which intersect to define two possible locations also shown in Fig. 4. The negative intersection point is discarded due to physical system constraints, leaving the positive intersection point to be obtained from (5) which independently determines the object's position in each dimension.

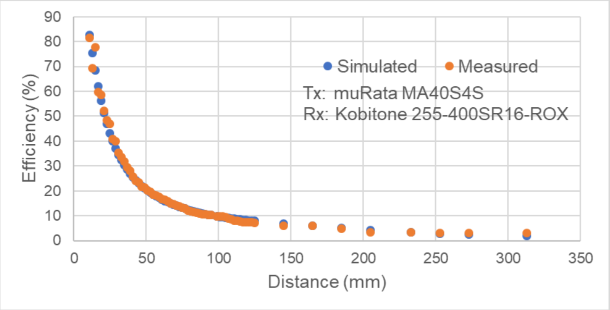


Fig. 5. Efficiency comparison over distance of simulated and measured results of rectangular linear array approximation.

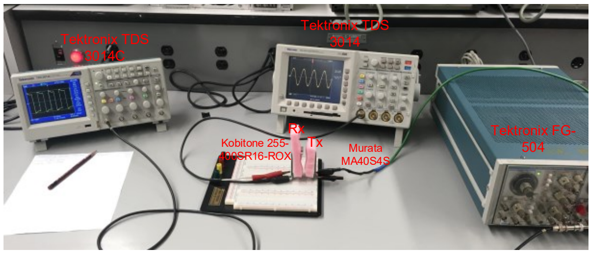


Fig. 6. Measured data acquisition setup with one receiving and one transmitting transducers.

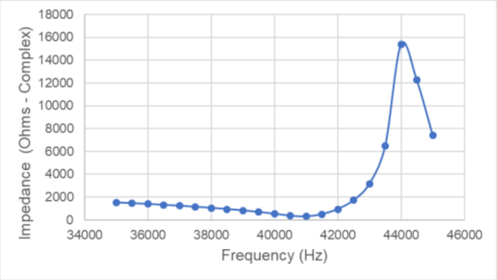


Fig. 7. Measured muRata MA40S4S complex impedance.

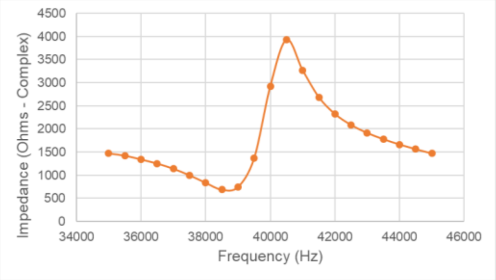


Fig. 8. Measured Kobitone 255-400SR16-ROX complex impedance.

III. SIMULATIONS AND MEASURED RESULTS

A. *Ultrasonic WPT*

The simulations were carried out in the linear domain using the kWaveTransducer class object within *k*-Wave Toolbox. Due to the rectangular dimensions of the kWaveTransducer class, a line approximation of the diameter of the transducers is used in place of a disc source mask. The kWaveTransducer class uses *N*-element array at user defined pitch to simulate the transducer characteristics (i.e. steering angle, apodization, focus distance) via beamforming delays provided by the user compiled input signal. The transducers are initially separated by 11mm, and a 40.7kHz square wave is sent through the transmitter with a sinusoidal wave being seen on the receiving end. As shown in Fig. 5, the ultrasonic wave propagation via the *k*-Wave Toolbox matches experimental results within 17 ppm. This provides experimental validation for the kWave Transducer class using a line approximation of a circular transducer solved in the linear domain and builds upon other *k*-Wave Toolbox experimental validations [13]. Fig. 6 shows the test setup. The system uses a muRata MA40S4S as the transmitting transducer, and the receiving transducer is a Kobitone 255-400SR16-ROX.

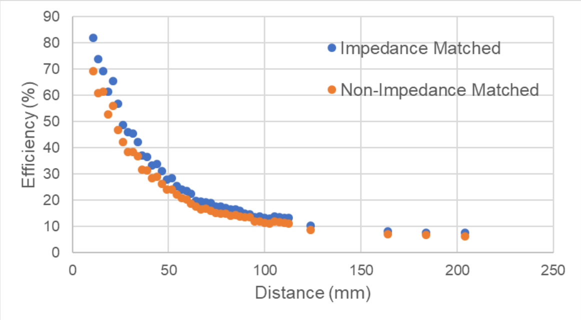


Fig. 9. Measured results of impedance and non-impedance matched circuit designs in transmission efficiency.

To ensure maximum WPT, an impedance matching circuit was developed. The setup was verified experimentally as shown in Fig. 7 and Fig. 8 where the impedance of the muRata and Kobitone transducers are measured against frequency. The operating frequency of 40.7kHz coincides with the series impedance of the muRata MA40S4S and the parallel impedance of the Kobitone 255-400SR16-ROX.

The nominal frequency for the transducers is 40.7kHz so in order to create a proper matching circuit the impedance data at this frequency was recorded. The LCR meter recorded the series resistance Rs as 180.5Ω, and the parallel capacitance Cp to be 7.037nF. Having the impedance of the transducers, the values for a matching parallel LC circuit were calculated [14], and the experimental data yielded values of 321.4μH and 28.576nF. In Fig. 9, the blue data curve indicates the system efficiency with the impedance matching circuit, and the red indicates the system without. Overall the system received an average of a 16.5 percent performance increase with the impedance matching circuit.

B. *Localization*

Fig. 10(a) shows the experimental setup used to accomplish 2D localization of a stationary 5mm diameter wooden dowel test object using two muRata MA58MF14-7N ultrasound transducers operating at a frequency of 58.8kHz in a medium of room-temperature air. The transducers are transformer-driven by Texas Instruments BOOSTXL-PGA460 and MSP-EXP430F5529LP evaluation boards which are in turn powered by a Tektronix PS280 DC power supply. The BOOSTXL-PGA460 boards are connected on a one-wire UART (OWU) bus that switches between each board successively and performs a burst/listen cycle containing five transmitting pulses.

A 15cm x 20cm test area was determined after consulting medical professionals who specialize in cardiovascular surgery

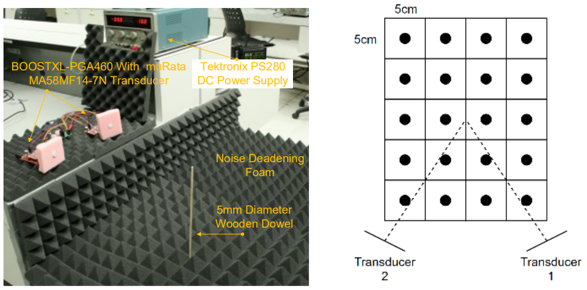
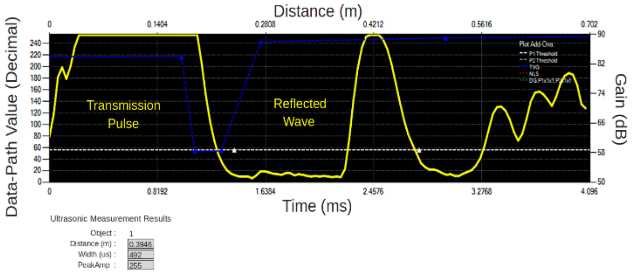


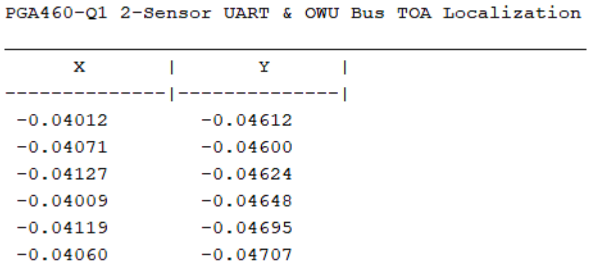
Fig. 10. (a) Experimental setup for 2D TOA localization, and (b) measuring grid layout (shown as proof-of-concept).



Ultrasonic Measurement Results

Object : 1
Distance (m) : 0.3946
Width (us) : 492
PeakAmp : 255

Fig. 11. GUI Data Monitor.



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PGA460-Q1 2-Sensor UART & OWU Bus TOA Localization
______________________________________________________
       X       |       Y       |
---------------|---------------|
 -0.04012          -0.04612
 -0.04071          -0.04600
 -0.04127          -0.04624
 -0.04009          -0.04648
 -0.04119          -0.04695
 -0.04060          -0.04707
```

Fig. 12. Serial monitor output for 2D localization.

and have extensive familiarity with the operation of endovascular catheters. This was divided into twenty points upon which the test object was moved, and position estimates were recorded and then averaged to determine overall accuracy in each dimension. The two transducers were oriented toward the center of the test area. An example of the testing area is shown in Fig. 10(b). The mono-static configuration of the transducers produces a transmission decay time that results in a test object minimum distance of approximately 30cm for five pulses at the given frequency.

The system uses the PGA460-Q1 EVM GUI to optimize the transducer settings and determine ideal parameters for one-way distance estimation. These settings include driving frequency and current, pulse count, time-varying gain, and threshold mapping. The most accurate distance estimation is obtained by fully saturating the return signal through analog front-end gain and mapping the threshold values as close to the base of the signal as possible while staying above the noise floor in order to prevent false positives. An example of the GUI Data Monitor output using the given test object is shown in Fig. 11.

After the GUI has been used to determine the ideal settings, the open-source IDE Energia is used to implement the 2D TOA localization using two boards on the OWU bus. Once the software has determined the approximate position of the object, the Energia serial monitor outputs the coordinates of the object for each dimension. Each board takes approximately ten milliseconds to switch and perform the burst/listen cycle of its transducer, process the data, and output the result to the serial monitor. This results in the output displaying each dimensional coordinate at approximately 10ms intervals. Fig. 12 shows the serial monitor output for our test object at one of the test points.

Table. 1. 10 sample average accuracy errors over test area.

Dimension/Distance	**Average Accuracy Error (mm)**
One-Way Distance	0.34
X-Coordinate	6.32
Y-Coordinate	4.27

Prior work [15] had used one ultrasound transmitter and four receivers to obtain 3D coordinate values of a spherical test object achieving a minimum of 2.47cm average accuracy error. Our proof-of-concept localization experiment used two transducers that operated as both transmitter and receiver to obtain 2D cartesian coordinate values using TOA. Our experiment yielded the following improved average accuracy errors for one-way distance as well as per dimension across the twenty test points shown in Table. 1.

IV. CONCLUSIONS AND FUTURE WORKS

We present an experimental testbed for simultaneously localizing a static object in 2D and wirelessly transferring power utilizing ultrasonic transducers for next-generation implantable biomedical applications. An ultrasonic wave propagation model has been developed using open-source MATLAB toolbox (k-Wave). Experimental validation of the WPT for a linear rectangular array was demonstrated at distances between 11mm to 310mm using commercially available transducers achieving 81.9 percent transfer efficiencies through air. The testbed includes a localization system incorporating backscatter-based TOA using two mono-static transducers on a burst/listen cycle using the PGA460-Q1 EVM and Energia software. One-way accuracy was optimized to within 0.34 mm with 6.32mm accuracy in the x-axis, and 4.27mm in the y-axis. The successful implementation of these sub-systems provides a thorough testbed for future use in a combined system for implantable medical devices. This method of testing utilizing off-the-shelf components and open-source software has not been done before.

Future work will seek to improve our localization system to three dimensions by introducing additional transducers operating in an alternate plane for localization of the test object tip. We will also implement a bi-static, open-top transducer configuration for increased sensitivity and eliminate the minimum-distance requirement of our design. Lastly, we will place our test object within a phantom containing multiple mediums of varying thicknesses in order to more closely mimic conditions and layering of the human body.

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