

Acoustic Energy Transmission on Mobile Sensors (AEToMS) in Closed (Pipe) Systems

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Abstract: This paper investigates acoustic energy transmission for wirelessly charging mobile sensors in enclosed systems using focused ultrasound. A test setup with a 32-element ring array and a spherical sensor was used. The sensor was localized using time-of-flight measurements. Two focusing methods (phased array and time reversal) were implemented and experimentally compared. The charging signals were analysed in terms of amplitude and energy. The time-reversal approach achieved better focusing quality and higher energy transfer.

Keywords: Ultrasound, mobile sensors, localisation, focusing, energy harvesting

Background and Motivation

Mobile wireless sensor networks offer a promising solution for optimizing process control in closed systems through holistic, local monitoring. Unlike stationary sensors, mobile units move with the process medium, enabling spatially and temporally resolved data collection (even in otherwise inaccessible regions). Wireless transmission of the collected data provides real-time, location-specific insights to enhance system control.

While modern low-power systems consume minimal energy in standby, active modes (e.g. sensing, processing, and transmitting) can significantly increase power demand. Despite energy-saving strategies, battery depletion remains a limiting factor. This challenge can be addressed via energy harvesting, including external wireless energy transmission.

Unlike commonly used inductive methods, this work explores an acoustic approach using ultrasound. A key advantage is that the interaction range can be significantly increased, which is achieved either by controlled beam shaping or by utilising reflections at system boundaries. In order to efficiently transfer energy for charging a mobile sensor, the acoustic energy can be focussed on its position and converted in electrical energy by using a piezoelectric transducer.

This paper addresses the investigation of various methods for acoustic localisation and focusing e.g., time-of-flight (TOF), phased array (PA), time reversal (TR), to develop a feasible concept for efficient acoustic energy transmission with optimized energy yield.

Experimental Setup

Based on initial design decisions, a first experimental setup was developed, including a sensor prototype and a cylindrical test environment (see Fig. 1). The sensor is a 25 mm SLA-printed sphere with six flush-

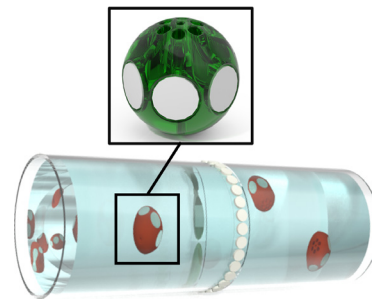


Fig. 1: Rendered image of the sensor (top) and multiple sensors in a pipe as sensor network (bottom).

mounted piezoelectric transducers in a ring configuration. These serve both as receivers for acoustic energy and as transmitters for localisation (via burst signals) as well as communication (via frequency-modulated acoustic signals). The test cylinder (PMMA, 110 mm diameter, 200 mm height) contains 32 circumferential piezoelectric transducers mounted on outer facets for consistent coupling. These transducers are used for sensor localisation, acoustic energy focusing, and reception of communication signals. The piezoelectric elements used in both the sensor and cylinder are ceramic disks (PIC255, 10 mm diameter, 2 mm thickness).

Electronic components such as microcontroller, T/R switch, and energy management system (including signal conditioning, harvesting IC, and storage) are externally implemented at this stage. The transducers are connected via cables to the signal generation, measurement, or energy management systems. A detailed description of the sensor and its energy management system can be found in [1].

For accurate positioning, the sensor is fixed on a

rigid wire and placed using a modified 3D printer. A MATLAB-based control software with a graphical user interface (GUI) was developed to operate the 3D positioning system, function generator, and digital oscilloscope, allowing automated measurement and frequency-modulated (FM) signal analysis for communication.

Signal acquisition is carried out using a four-channel digital oscilloscope, while synchronous output on 32 channels is generated via pulse-width modulation (PWM) using an FPGA evaluation board. Custom amplifier stages increase the signal amplitude to ± 30 V and apply low-pass filtering to reconstruct the acoustic waveforms. Additionally, COMSOL and LTSpice simulations are used for system analysis and optimisation. This setup provides the foundation for evaluating different localisation and focusing methods to improve focusing efficiency and charging performance.

Methods of Localisation and Focusing

Depending on the application, sensors may face constraints (e.g., limited space), requiring functional differentiation. The choice of acoustic energy transmission depends on whether the sensor actively transmits signals or functions passively. Initial tests confirmed that short acoustic transmissions are energetically feasible, motivating a focus on active signal emission. Two acoustic focusing methods are considered: phased array (PA) and time reversal (TR).

In PA, time-delayed signals from the external array produce constructive interference at a defined focal point [2] (as schematically shown in Fig. 2, step 3). This enables spatial selectivity without mechanical alignment, but requires precise knowledge of sensor position and medium properties. The method is sensitive to inhomogeneities and multipath effects.

Accurate localisation is thus essential. A common approach uses time-of-flight (TOF) or time-difference-of-arrival (TDOA) techniques. The sensor emits a signal through all its transducers, which is detected by external receivers (see Fig. 2, step 1). Based on signal arrival times and the known sound speed, the sensor position is estimated by triangulation or trilateration (Fig. 2, step 2). These methods are efficient, but their accuracy depends on precise time-picking and reliable sound speed. Reflections, multipath propagation, and medium inhomogeneities (e.g., temperature or concentration gradients) can obscure the direct signal and reduce accuracy. In sensor networks, mutual interference or occlusion can make signal interpretation even more difficult.

TR techniques provide a robust alternative in complex environments. Unlike PA, TR requires no prior localisation. Instead, the sensor emits a pulse, which is recorded over time by the external array, including

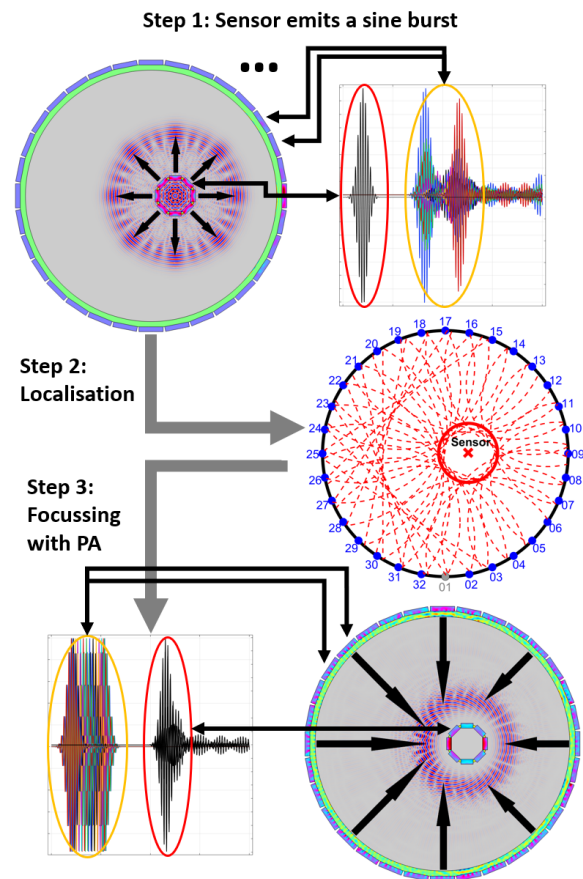


Fig. 2: Schematic procedure of the phased array focusing method: (Step 1) the sensor emits a pulse, (Step 2) the position is localized, (Step 3) acoustic energy is focused using time-delayed signals.

system-internal reflections (as schematically shown in Fig. 3, step 1). These signals are then time-reversed and re-emitted. Due to acoustic reciprocity, the wavefronts retrace their original paths and refocus at the source location [3] (Fig. 3, step 2).

This inherent property allows the method to compensate for inhomogeneities in the medium and to mitigate multipath effects, making it particularly well-suited for scattering or structurally complex environments [4]. Additionally, the presence of multiple reflections and scatterers can even enhance the focusing accuracy [5], which is advantageous for future applications in sensor networks. However, the method requires the initial calibration procedure and the time-reversed re-emission of the recorded signals, which inherently takes more time than phased array-based focusing. As a result, the achievable focusing rate (the number of focus events per second) is significantly lower.

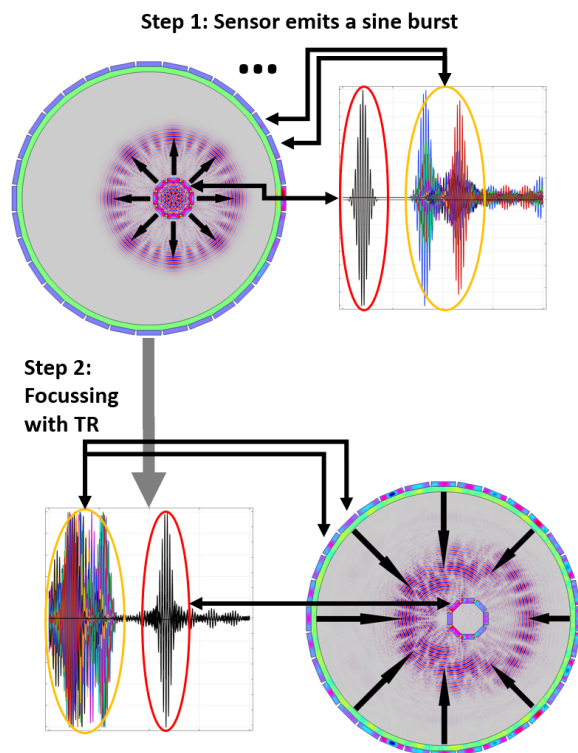


Fig. 3: Schematic procedure of the time reversal focusing method: (Step 1) the sensor emits a pulse, (Step 2) acoustic energy is focused using time-reversed signals.

Experimental investigations

For the experimental investigations, the sensor was positioned at various predefined locations along the x-axis within the water-filled cylinder, aligned with the plane of the external piezoelectric array. To enable acoustic focusing using either the PA or TR method, the sensor first emits a short sinusoidal burst signal (1 MHz, 5 cycles) simultaneously through all of its transducers. The resulting wave propagates radially through the medium and is recorded by the surrounding receiver array. The recorded signals are subsequently used for both localisation and TR-based focusing. Since accurate localisation is a prerequisite for the phased array approach, the sensor position was estimated based on the measured TOF of the received signals.

Tab. 1 presents the localisation results for selected sensor positions. To assess accuracy, the Euclidean distance between the true and estimated positions was calculated, yielding errors ranging from 0.39 mm to 2.56 mm, correspond to approximately 0.26 to 1.73 times the wavelength of the 1 MHz signal in water ($\lambda \approx 1.48$ mm). Relative to the cylinder's diameter (maximum possible error), this corresponds to devi-

Tab. 1: Localisation with TOF.

True position [mm] (x/y)	Estimated position [mm] (x/y)	Euclidean error [mm]
0/0	2.55/0.26	2.56
10/0	9.63/0.3	0.39
20/0	18.62/-0.87	1.52

ations between 0.75 % and 4.92 %. This indicates that subwavelength localisation is achievable under favourable conditions, while worst-case deviations remain within approximately two wavelengths. These results demonstrate a spatial resolution that is consistent with the expected limits of TOF-based localisation methods.

To ensure the comparability of the results, the PA technique was applied using the actual target position instead of the calculated one, which was subject to errors. A time-shifted sinusoidal burst with a frequency of 1 MHz and 5 cycles was used for the PA focusing signal. This choice accounts for the duty cycle used during the calibration of the TR signals and enables a fair comparison between both methods. Depending on the position, the transmission of the time-delayed PA signals was completed after approximately 50 μ s. In contrast, a time window of 500 μ s was selected for the calibration of the TR signals, corresponding to approximately three complete round trips of the acoustic wave across the cylinder. Fig. 4 compares the signal amplitudes of all transducers of the sensor at the position (10/0) at the respective focusing times. While the moment of maximum focusing occurred at around 43 μ s for the PA method, it was observed at approximately 503 μ s when using the TR method.

When comparing results, the maximum peak value (voltage amplitude) across all transducers is considered as a primary indicator of spatial and temporal energy concentration. Higher peak amplitudes reflect more effective constructive interference of acoustic waves at the focal point, which correlates with improved focusing quality. Tab. 2 presents the maximum peak values obtained for selected focal positions. For these representative cases, the TR method achieves a substantial increase in amplitude, ranging from 53.1 % to 80.6 % compared to the PA approach.

However, the maximum amplitude does not directly reflect the amount of energy available at the focal point. To more robustly characterise the performance of energy transfer, this comparison is supplemented by evaluating the root mean square (RMS) over a defined time window. Since the sensor is equipped with six

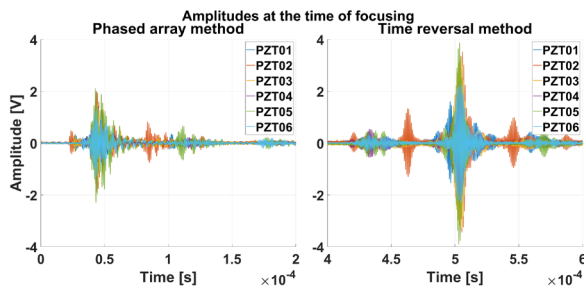


Fig. 4: Signal amplitudes of all transducers of the sensor at the position (10/0) at the time of focusing for two methods: phased array (left) and time reversal (right).

Tab. 2: Comparison of the maximum peak value.

Position (x/y) [mm]	Max amplitude PA [V]	Max amplitude TR [V]
0/0	3.25	5.09
10/0	2.17	3.91
20/0	2.5	3.82

transducers, the RMS value is calculated for each transducer within a 10 μ s window centred around the individual peak amplitude and subsequently averaged. Tab. 3 presents the results of this RMS analysis. Again, the TR method shows a consistent advantage across all focal positions, with relative increases in RMS between 100.86% and 129.23% compared to the PA approach. This indicates that more usable energy is concentrated within the analysed time window, suggesting improved energy harvesting potential.

Summary and Outlook

This work explored two acoustic focusing techniques (phased array and time reversal) for wireless energy transmission to mobile sensors in enclosed systems. PA-based focusing requires prior localisation, for which a TOF-based algorithm achieved subwavelength accuracy. Both methods were theoretically analysed and experimentally tested in a 2D setup. TR showed con-

Tab. 3: Comparison of the averaged RMS value.

Position (x/y) [mm]	Averaged RMS PA [V]	Averaged RMS TR [V]
0/0	1.03	2.08
10/0	0.68	1.56
20/0	0.48	0.99

sistently higher peak amplitudes and RMS values across all sensor transducers, indicating more effective focusing and greater energy availability within a defined time window. These results lay the groundwork for optimising charging performance and assessing system efficiency in future studies.

Further research will extend the current 2D system to 3D. To achieve this, chaotic cavities or acoustic lenses may be employed to increase transducer aperture. Under such conditions, conventional TOF localisation and PA focusing become unreliable, motivating the use of data-driven approaches such as machine learning [6]. Additionally, iterative time reversal [2] offers adaptive, tracked focusing without explicit localisation, with potential for selective targeting via decomposition of the time-reversal operator (DORT) in multi-sensor systems. The long-term objective of this work is the development of a robust, energy-autonomous mobile sensor network.

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