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Time-efficient low power time/phase-reversal beamforming for the tracking of ultrasound implantable devices

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***Abstract*—Ultrasound (US) has recently gained attention for powering and communication with implantable devices due to its short wavelength and low attenuation. However, beam misalignments cause a sharp decrease in the amount of transferred power and quality of communication. This work investigates a telemetry protocol that relies on the difference in the phase of the received backscattered signal to precisely focus the US on the implantable device and track it over time. The interrogation signal is generated by a linear phased array probe, and the receiver is a pre-charged collapse-mode Capacitive Micromachined Ultrasound Transducer (CMUT) connected to a load modulation circuit. Using the time/phase reversal tracking algorithm, the RX was located within 300 ms after the first modulation was detected. The ability of the algorithm to track the RX while it is moving was also tested, showing that it can reliably track it up to a speed of 1 mm/s.**

***Index Terms*—CMUT, Capacitive Micromachined Ultrasound Transducers, Backscattering, Tracking**

I. Introduction

Ultrasound (US) has recently gained attention for powering implantable devices and exchanging information with them due to its low attenuation in the body and its short wavelength, which allows precise focusing. US power can be delivered to an US receiver on an implantable device using either a single element transducer or a phased array transducer. While using a single element transducer multiple implants can be powered, a significant amount of power will be lost at the locations in between the implants, also increasing the risk of possible damage to the surrounding tissue. In addition, due to the inherent nature of the sound field of a single element transducer, the amplitude of the echo signal has a series of maxima and minima in the region between the surface of the transducer and the last maxima, named near field. This introduces a minimum distance at which the implant can be placed to avoid unreliable operation. On the other hand, with a phased array transducer, the output power is focused on the target implant, maximising the power transfer efficiency. In addition, communication and power transfer to a single implant at a time is also preferred. However, a downside of this method is its sensitivity to beam misalignments that causes a sharp decrease in the amount of transferred power and quality of communication [1].

In a real case scenario, the position of the US receiver in the body is not known a priori, and a traditional ultrasound scan should be performed to locate the implant. In addition, the position of the implant with respect to the external transmitting transducer changes over time due to motions of the body which, depending on the location, can reach values up to $3\,\mathrm{mm/s}$ [2]. Furthermore, in the case of a hand-held US transducer, the small movements of the hand will also play a role, although this effect could be limited by using an US patch fixed on the skin in the proximity of the implant location [3], [4]. To overcome these limitations, a tracking algorithm that locates the implant and tracks it over time is therefore necessary to maintain a high link efficiency for reliable powering and communication.

Localisation by means of US can be classified into two main categories: active tracking and passive tracking [5]. Active tracking requires the active driving of the US element on the implant, while passive tracking uses an US wave sent by an external US transmitter that is backscattered by the US element. Active tracking offers a greater penetration depth since the US travels only in one direction through the media, but it requires considerably more power than passive tracking. In this work, we investigate the use of a passive tracking method for localising an ultrasonic implantable device. Most of the transmit beamforming methods require prior knowledge of the implant position to direct the US beam of the linear phased array to the implantable device [6]. Here, we investigate the use of a telemetry protocol that relies on the phase difference of the US signal backscattered by the implant and received

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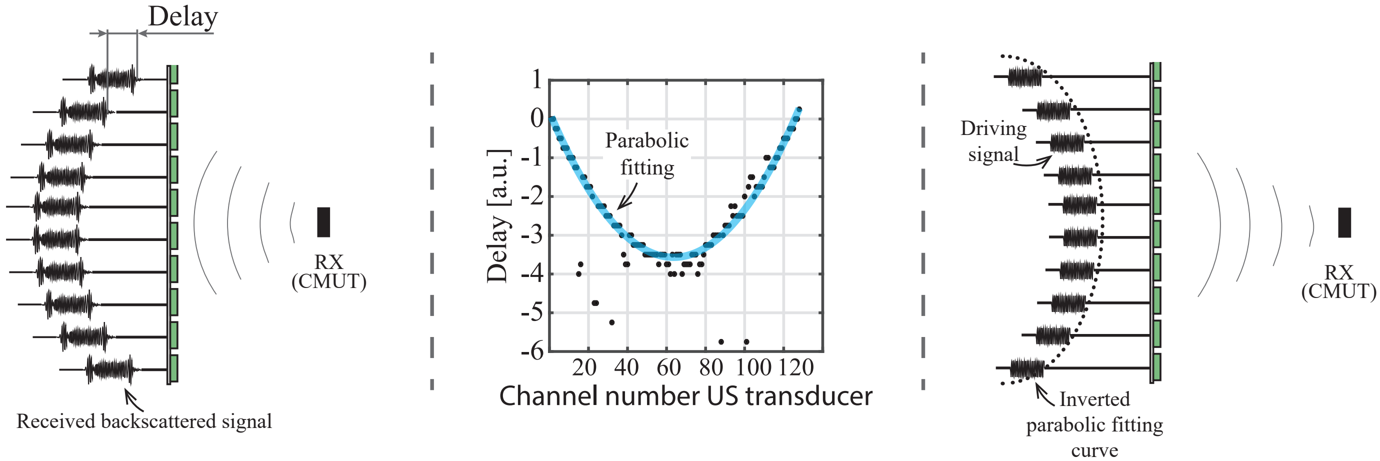

Fig. 1. Schematic of working principle of time/phase reversal algorithm. (a) Schematic of backscattered signal from the RX received by each array element. (b) Example of delays obtained with calculating the cross-correlation between the signal received by each channel and a reference channel. The light blue curve indicates the parabolic fitting. (c) Schematic of driving conditions for the ultrasound transducer obtained by inverting the fitted parabolic curve.

by each element of a linear phased array to precisely focus the US beam on the implant and create a tight ultrasound link robust against small movements.

II. Time/Phase Reversal Telemetry Protocol

To focus an US beam using a linear array on a point in space, time delays are provided to each element of the array. Reversing this principle, when a phased array of ultrasound transducers receives ultrasound waves from a point source, each element of the array senses this signal at different moments in time (Fig. 1(a)) [7]. Using this principle, the time/phase reversal algorithm estimates the location of the source from the delays of the signal coming from that source. With the time reversal method, the measured time delays are inverted and applied to the linear array elements. In addition to time reversal, phase reversal calculates the delay difference between the signal received by each linear array element with respect to a reference element, inverts them, and feeds them to each array element with a delay of zero for the reference element.

In this work, the time/phase reversal algorithm is used to develop a passive tracking algorithm that uses the backscattered signal from a pre-charged Capacitive Micromachined Ultrasound Transducer (CMUT) array. The telemetry circuit used here is based on our prior work [8], in which the interrogation signal is generated by a linear phased array probe (TX) and the receiver (RX) is a pre-charged collapse-mode CMUT.

A. Experimental setup

The experimental setup (Fig. 2) used to validate the protocol consists of the TX (Philips, L7-4 linear probe), the RX, a load modulation circuit, and a gel phantom (Rayher Hobby GmbH). The TX consist of 128 elements of size $7\,\mathrm{mm} \times 0.28\,\mathrm{mm}$ and a $25\,\mu\mathrm{m}$ kerf. It is connected to a Verasonics ultrasound research platform, which allows programming the ultrasound parameters and access to raw ultrasound data using MATLAB. The RX is a pre-charged collapse-mode CMUT of size $0.84\,\mathrm{mm} \times 7.4\,\mathrm{mm}$, where pre-charged means that charge is trapped in one of the dielectric layers, such that no external bias voltage is required [9]. The RX consists of 6 CMUT elements in parallel, each consisting of 56 cells. The width and length of the TX focus are $0.88\,\mathrm{mm}$ and $17\,\mathrm{mm}$ respectively which, compared to the size of the receiver, highlights the importance of accurate focusing. A gel phantom made of $95\,\%$ paraffin oil and $5\,\%$ organic constituents is used as medium between the TX and RX to mimic the ultrasound propagation in human tissue [10]. The RX is connected to a load modulation circuit which modulates the signal backscattered by the RX every other incoming ultrasound burst with a time delay proportional to the voltage on a storage capacitor which, in turn, is proportional to the amount of energy received by the CMUT. Refer to [8] for more details on how the load modulation circuit is implemented.

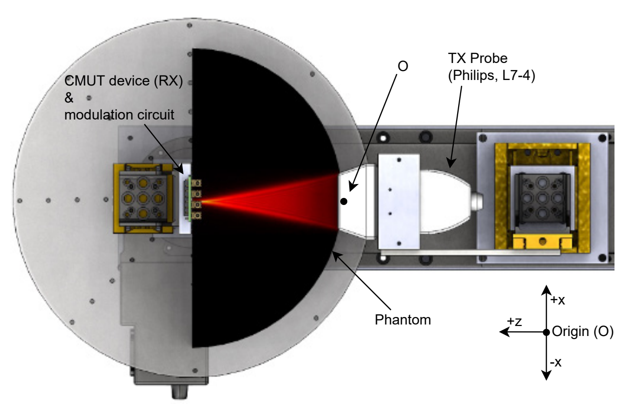

Fig. 2. Schematic of the experimental setup

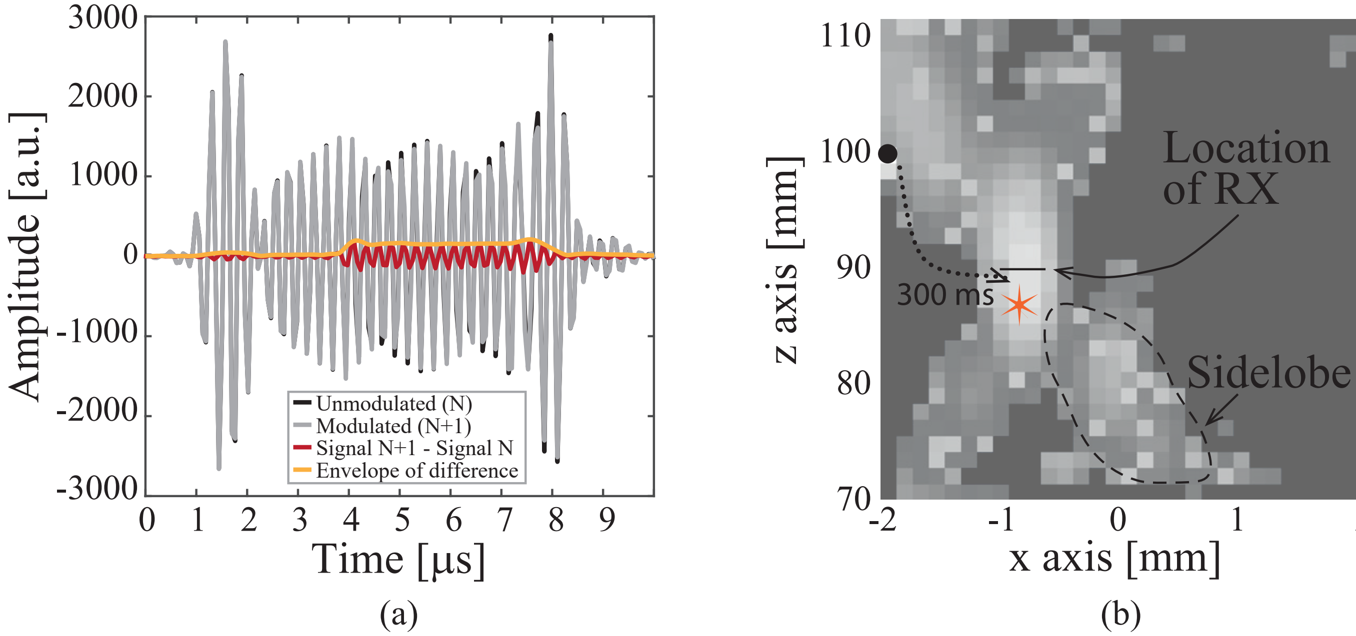

Fig. 3. (a) Example of modulated and unmodulated backscattered signals received by the TX, together with the differential signal and its envelope. (b) Reference heatmap obtained with traditional scanning of the ROI. The brightest regions indicate point where modulation of the backscattered signal was detected. The RX is placed approximately around coordinate (-1, 90). The black dot is the point of the first modulation and good delays fitting. It takes about 300 ms from this point to focus on the receiver location.

B. *Tracking algorithm*

The tracking algorithm developed in this work is based on the time/phase reversal method and modulation of the backscattered signal. A region of interest (ROI), which contains the target (RX), is defined, and a coordinate system is defined. Two consecutive ultrasound bursts of 24 cycles with a frequency of $4\,\mathrm{MHz}$ and a pulse repetition frequency of $500\,\mathrm{Hz}$ are sent by the TX and focused on the first coordinate point of the coordinate system. They are then backscattered by the RX or the surrounding area and checked for pulse width modulation by computing the envelope of the differential signal. An example of two consecutive backscattered signals received by the TX is shown in Fig. 3(a). The two signals are distorted due to reflections and scattering in the phantom, and it is difficult to detect the modulation since the two signals are largely overlapping. However, computing the differential signal and its envelope allows to determine if the signal has been modulated and, most importantly, it rejects common-mode interferences and low-frequency artifacts, making this method robust.

In the case of no modulation, the focus is moved to the next point in the coordinate system. If modulation is observed, the delays associated with the modulated bursts received by each TX channel, are detected by calculating the cross-correlation with respect to a reference TX channel, in this case the 1$^{\mathrm{st}}$ one. This step corresponds to the implementation of the phase reversal technique, and it is favoured by the sharp rising edge of the differential signal. To focus on a single point, the delays associated with each TX channel must follow a 2$^{\mathrm{nd}}$ order relationship, therefore they are fitted with a parabolic curve (Fig. 1(b)). The residuals of the fitting are then calculated, and if the deviation between the fitting and the measured delays is less than $8\,\%$, the curve is inverted and the time delays are applied to each TX channel (Fig. 1(c)). In this way, the ultrasound is precisely focused on the active RX region. In case the deviation is more than $8\,\%$, the fitting is discarded, and the TX focus moves to the next coordinate point.

III. Results and Discussion

A. *Focusing on the receiver*

Fig. 3(b) shows the heatmap generated by scanning the whole ROI. The ROI is composed of 30×30 pixels and is obtained with traditional scanning, which takes approximately 3 minutes for a region of this size. In this figure, the brighter areas indicate the points in which modulation is observed, and the brightness is proportional to the pulse width of the backscattered signal modulated by the load modulation circuit, therefore proportional to the received power. The brightest region, approximately at coordinate (-1, 90), corresponds to the location of the RX. Using the time/phase reversal tracking algorithm, the location of the RX was found within 300 ms after the first modulation was detected (black dot in Fig. 3(b)) and a good fitting of the delays was obtained, independently of its location. However, the delay taken by the system to process the backscattered signal and to focus on the right location is due to limitations of the system itself. Specifically, the processing of the data including its transfer from the hardware sequencer of the Verasonics to the MATLAB environment in the host computer, where the tracking algorithm runs, takes about $300\,\mathrm{ms}$. This delay can however be decreased by implementing the algorithm on dedicated hardware such as a FPGA or a GPU based system.

Since the search for the position of the RX is essentially a search for the maximum of the pulse width modulation, it can be assumed that other maximum search algorithms can be used. A 2-D binary search [11] and a method based on the trailing of the increase in the pulse width were implemented as a comparison. The latter method consists of scanning a small area of the heatmap and, depending on which sub-section of this area has longer pulse widths, therefore a higher received power, the scanning area is shifted towards that direction at the next iteration until reaching the (local) point of maximum received power. However, both these methods failed to find the location of the RX because the heatmap often contains side lobes, as it can be seen in Fig. 3(b), which function as local maxima and are therefore identified by the two search methods as the location of the receiver. On the other hand, the time/phase reversal algorithm is faster and robust enough to correctly locate the receiver.

Eventually, obtaining the heatmap of the ROI is not necessary to localise the implant with the time/phase reversal method, although it was used in this work as a reference to confirm that the algorithm was focusing the US beam on the correct location and to compare the speed of the two methods. Additionally, because the TX is a linear array, therefore its focus cannot be moved in the elevation plane, the tracking of the RX in this work is limited by the respective position of the TX and the RX that must be parallel to each other and the focus of the TX needs to be in the same plane as the RX.

B. Testing the tracking of the implant against micromovements

Once the receiver has been located, the link between the TX and the RX must be maintained and be able to compensate for small body movements. To test this, the CMUT receiver was mounted on a 3D motorised stage and submerged in a water tank at about 130 mm from the TX. For this experiment, water was used as a medium because the gel phantom does not allow for the freedom of movement of the RX in 3D. The water tank has a window made of a $30\,\mu\mathrm{m}$ thick PET foil to allow interfacing the TX from outside of the tank. The motorised stage was programmed to move at a constant speed between $-2\,\mathrm{mm}$ and $2\,\mathrm{mm}$ in the x direction with respect to the initial position of the RX in space. The initial speed of the RX was set to $0.2\,\mathrm{mm/s}$ and increased after successfully tracking the target (RX). An example video was recorded during one of the experiments and is available at [12]. The maximum speed at which reliable tracking of the RX was achieved was $1\,\mathrm{mm/s}$, and also in this case, is limited by the Verasonics system as explained in the previous section.

IV. CONCLUSION

In this work, the time/phase beamforming method was implemented for the passive localisation of an ultrasound receiver through load modulation. Using this algorithm, the receiver was located in $300\,\mathrm{ms}$, making it robust against body movements. In addition, the algorithm was able to reliably track a receiver moving at a speed up to $1\,\mathrm{mm/s}$. It is expected that, by using dedicated hardware, the response time and the maximum trackable speed will improve. Future work will focus on testing the algorithm in inhomogeneous medium and expanding the functionality of the link with communication capabilities to transfer information to and from the implant.

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REFERENCES

[1] D. K. Piech, B. C. Johnson, K. Shen, M. M. Ghanbari, K. Y. Li, R. M. Neely, J. E. Kay, J. M. Carmena, M. M. Maharbiz, and R. Muller, “A wireless millimetre-scale implantable neural stimulator with ultrasonically powered bidirectional communication,” *Nature Biomedical Engineering*, vol. 4, no. 2, pp. 207–222, 2020.

[2] G. Shafiq and K. C. Veluvolu, “Surface chest motion decomposition for cardiovascular monitoring,” *Scientific reports*, vol. 4, no. 1, pp. 1–9, 2014.

[3] J.-É. S. Kenny, C. E. Munding, J. K. Eibl, A. M. Eibl, B. F. Long, A. Boyes, J. Yin, P. Verrecchia, M. Parrotta, R. Gatzke, P. A. Magnin, P. N. Burns, F. S. Foster, and C. E. M. Demore, “A novel, hands-free ultrasound patch for continuous monitoring of quantitative doppler in the carotid artery,” *Scientific Reports*, vol. 11, no. 1, 2021.

[4] C. Wang, X. Chen, L. Wang, M. Makihata, H.-C. Liu, T. Zhou, and X. Zhao, “Bioadhesive ultrasound for long-term continuous imaging of diverse organs,” *Science (New York, N.Y.)*, vol. 377, no. 6605, pp. 517–523, 2022.

[5] T. D. Than, G. Alici, H. Zhou, and W. Li, “A review of localization systems for robotic endoscopic capsules,” *IEEE Transactions on Biomedical Engineering*, vol. 59, no. 9, pp. 2387–2399, 2012.

[6] S.-C. Wooh and Y. Shi, “Optimum beam steering of linear phased arrays,” *Wave Motion*, vol. 29, no. 3, pp. 245–265, 1999.

[7] O. T. Von Ramm and S. W. Smith, “Beam steering with linear arrays,” *IEEE Transactions on Biomedical Engineering*, vol. BME-30, no. 8, pp. 438–452, 1983.

[8] S. Kawasaki, I. Subramaniam, M. Saccher, and R. Dekker, “A microwatt telemetry protocol for targeting deep implants,” in *IEEE International Ultrasonics Symposium (IUS)*. IEEE, 2021, Conference Proceedings.

[9] S. Kawasaki, Y. Westhoek, I. Subramaniam, M. Saccher, and R. Dekker, “Pre-charged collapse-mode capacitive micromachined ultrasonic transducer (cmut) for broadband ultrasound power transfer,” in *2021 IEEE Wireless Power Transfer Conference (WPTC)*. IEEE, 2021, Conference Proceedings.

[10] Y. Westhoek, “Ultrasound energy transfer using charged cmuts,” Manuscript, Delft University of Technology, 2020. [Online]. Available: http://resolver.tudelft.nl/uuid:74a07486-73c2-4457-8261-7161acb46c60

[11] A. Lin, “Binary search algorithm,” *WikiJournal of Science*, vol. 2, no. 1, pp. 1–13, 2019.

[12] M. Saccher, S. S. Lolla, S. Kawasaki, and R. Dekker, “Video recording associated with the publication: Time-efficient low power time/phase-reversal beamforming for the tracking of ultrasound implantable devices,” 2022. [Online]. Available: https://data.4tu.nl/articles/dataset/Video_recording_associated_with_the_publication_Time-efficient_low_power_time_phase-reversal_beamforming_for_the_tracking_of_ultrasound_implantable_devices/21081937/1