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Toward Real Time Backward-Mode Pulsed Magnetomotive Ultrasound

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***Abstract*—Magnetomotive ultrasound (MMUS) is an emerging technique to image *in vivo* magnetic nanoparticle (MNP) distribution, which is challenging to conventional B-mode ultrasound, and has shown its potential in extravascular ultrasound molecular imaging, monitoring of magnetic nano-drug delivery, and sentinel lymph node identification. To date, MMUS is mainly implemented in forward mode where the imaging object must lie in between an ultrasound probe and an electromagnet, and the imaging frame rate is low, both of which hinder its clinical translation. To facilitate clinical translation of MMUS, here we move toward the development of a real time backward-mode pulsed magnetomotive ultrasound system based on an ultrasound research engine, Prodigy (S-Sharp Corp., Taiwan), featuring an MMUS probe integrating a linear array and an electromagnet. The MMUS probe facilitates the backward-mode MMUS, improving the portability of MMUS. All the processing exploits the fast Prodigy-to-MATLAB interface, PSRT, automatically streaming beamformed ultrafast baseband data to MATLAB for post-processing and image display. Overall, we demonstrate that the imaging frame rate of our MMUS system can achieve 3.4 Hz with free hand scanning, which is about nine time faster than those of the previously reported systems. We believe that such handheld and toward real-time capability would push MMUS toward clinical usage.**

Keywords—magnetomotive ultrasound, magnetic nanoparticles, molecular imaging, real time

I. Introduction

Recently, nanoparticles have been used as contrast agent to image the human body for molecular imaging. Conventional ultrasound B-mode imaging cannot visualize nanoparticles due to their weak backscattering. Oh et al. [1] first demonstrated that magnetomotive ultrasound (MMUS) can be used to detect the magnetic nanoparticles. By applying an external oscillating magnetic field, motion is induced within the tissue where the magnetic nanoparticles accumulate; then such motion can be detected via motion tracking using ultrasound imaging and magnetic nanoparticles can be localized. MMUS has shown its potential in extravascular ultrasound molecular imaging, monitoring of magnetic nano-drug delivery, and sentinel lymph node identification.

Ultrasound imaging is a popular medical imaging technique because it is real time, portable, and cost-effective. However in the case of MMUS, the external electromagnet is difficult to carry and thus not portable. In addition, the imaging speed of the currently reported MMUS system is slow and thus is not suitable for real time imaging. These two main problems prevent MMUS from clinical usage.

In this work, we move toward the development of a real time backward-mode pulsed MMUS system based on an ultrasound research engine, Prodigy (S-Sharp Corp., Taiwan) and a custom-made MMUS probe allowing free-hand scanning. we use the backward-mode setup of MMUS. Forward-mode MMUS refers to the MMUS setup where the imaging object is in between the ultrasound transducer and the electromagnet while backward-mode MMUS uses a transducer integrated with a electromagnet, which is our MMUS probe design and shown in Fig 1. Our design not only ensures the external magnetic field is always applied in the field of view of the transducer, but also lighten the weight of the electromagnet since it does not need such strong focused magnetic field comparing to that of the previously reported forward-mode MMUS. The backward-mode setup makes handheld and free-hand scanning MMUS possible. In addition, our previously proposed MMUS detection algorithm [2] is optimized and implemented on the Prodigy to MATLAB interface, PSRT, in which GPU is used to perform real-time beamforming and multi-thread CPU processes are used to perform the MMUS detection algorithm. Such implementation exploits the parallel characteristic of the algorithm and provides performance speedup.

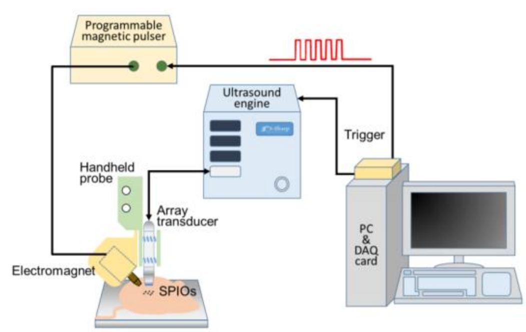

Fig. 1. System setup of our proposed backward-mode MMUS.

II. System Setup toward real-time implementation

The backward-mode MMUS imaging system is shown in Fig. 1. The system features a MMUS probe integrating a 7.5-MHz ultrasound linear array transducer with an electromagnet. Our MMUS probe design ensures that the magnetic field created by the electromagnet always covers the field of view of the linear array, which is unlike that in the reported forward mode setup where focused magnetic field is used and thus the field of view is limited. Note that for our MMUS probe, a custom-made holder was used to keep the electromagnet in place and prevent the vibration of electromagnet from propagating to the transducer and thus creates motion artifacts in MMUS images.

A programmable magnetic pulser was used to generate electric current sent to the electromagnet. The pulser could generate maximum 160 V and 25 A current. The maximum magnetic field generated by the electromagnet is 0.4 Tesla.

In each firing, a special designed pulse sequence was sent by the DAQ card to the programmable magnetic pulser. Each fired pulse sequence was designed to be 5 impulse cycles with each pulse duration of 10 ms (100 Hz). One MMUS image was obtained per firing. We let the electromagnet cool down 50 ms between each pulse sequence so that the electromagnet would not be overheated. That is, the repetition rate of the pulse sequence is 10 Hz.

The reason of designing such high frequency pulse (100 Hz) is that there are many vibration noises that could be identified as the induced motion from the nanoparticles by mistakes, e.g. respiratory motion, heart rate motion, background vibration. Therefore, we designed the pulse to be 100 Hz so that it could be easily extracted by a simple frequency selective filter.

The ultrasound system performed ultrafast plane wave imaging at 1.25 kHz frame rate. Higher frame rate gives better imaging quality but need more computational power. To balance imaging quality and speed, we found that 1.25 kHz frame rate yields acceptable quality and speed.

In order to perform the tracking algorithm in real-time, simple and parallelable algorithms were used. First, we performed displacement tracking using lag-one autocorrelation along the slow-time axis on each pixel. Such algorithm could track subwavelength displacement of the tissue. Second, we used a high-pass filter with a cutoff frequency of 80 Hz to extract the target displacement signal. Last, we designed a matched filter according to the pulse sequence we designed. Matched filtering acted as a sequence detector that helped to detect specific signal pattern and to determine the region where the nanoparticles was laden.

All three algorithms were performed along the slow-time axis in each pixel and thus could be executed in parallel. In Prodigy (S-Sharp Corp., Taiwan), a GTX 1080Ti GPU was used to perform real-time ultrasound beamforming, and multi-threading on an i5-7700K CPU was employed to execute the algorithm in parallel on each pixel. The Prodigy-to-MATLAB interface was used to send the beamformed data from ultrasound scanner to MATLAB; then the detection algorithm was written in MATLAB and executed by CPU.

III. Experimental Results

3% gelatin phantoms were made and injected with 50 mg/ml superparamagnetic iron oxide (SPIO) nanoparticles. The SPIOs were laid in the middle of the phantom so that the induced motion and the associated shear wave propagation could be properly observed. 0.5% cellulose particles were also added and acted as ultrasound scatterers.

The system could compute one full MMUS image in 0.47 sec on an image size of 25 x 25 cm (332 x 128 pixels). If matched filtering was not applied, an image could be formed in 0.29 sec. Fig 2. shows the result of MMUS detection algorithm. The nanoparticles were laid in the middle of the phantom. The MMUS detection image presented the region of SPIO nanoparticles in color similar to color Doppler imaging. The higher the value indicated that the pixel had a higher probability of being the region of magnetic nanoparticles. The imaging depth could reach at least 3.5 cm.

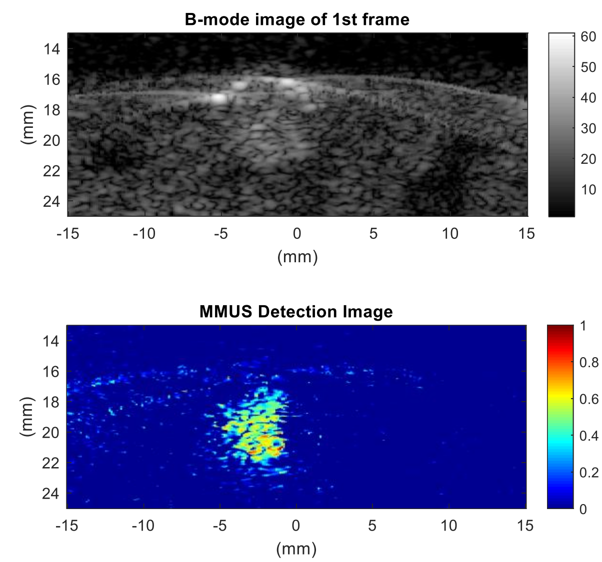

Fig. 2. Phantom experimental results of MMUS imaging. The magnetic nanoparticles were laid in the middle of the phantom.

The user interface also could overlay the MMUS images on conventional B-mode images, as shown in Fig. 3, so that we could display the detected MMUS image and the structural image at the same time. It was easy to tell that the magnetic nanoparticles were located in the middle of the phantom.

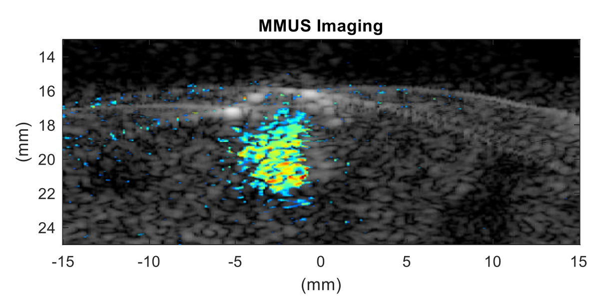

Fig. 3. MMUS detection image overlaid on a conventional B-mode image.

We compared the imaging speed with that of the previously reported MMUS system. M.M. Hossain et al. [3] used singular vector decomposition as a blind source separation algorithm to further increase the resolution of MMUS detection at the cost of detection speed. M. Evertsson et al. [4] implemented their MMUS detection algorithm in an online fashion, but their system is a forward-mode MMUS system which is not capable of free hand scanning and not suitable for clinical translation. Fig 4. shows the comparison of the imaging speed.

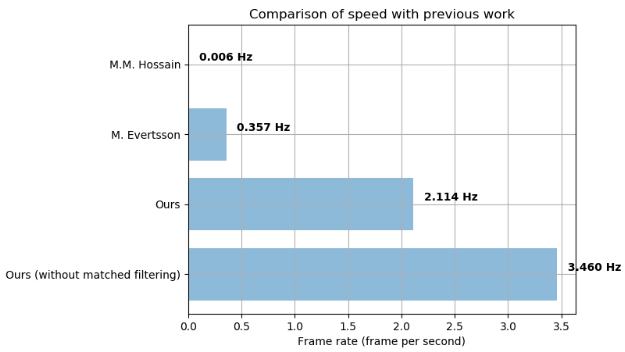

Fig. 4. Speed comparison of different MMUS systems.

IV. Conclusions

In this work, we demonstrate that our proposed backward-mode free-hand scanning MMUS system is capable of imaging at 3.46-Hz frame rate. We believe that such a toward real time design, at least 3.5-cm penetration, large field of view, and the capability of free-hand scanning will push MMUS toward clinical usage. Future work will focus on utilizing GPU to push the algorithm even faster, and further reducing the weight of the electromagnet.

Acknowledgments

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References

[1] J. Oh, M. D. Feldman, J. Kim, C. Condit, S. Emelianov and T. E. Milner, “Detection of magnetic nanoparticles in tissue using magneto-motive ultrasound,” Nanotechnology, vol. 17, no. 16, pp. 4183-4190, 2006.J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] M. C. Lu, J. Y. Houng and M. L. Li, “Backward-Mode Ultrafast Pulsed Magnetomotive Ultrasound,” 2017 IEEE International Ultrasonics Symposium Proceedings.

[3] M. M. Hossain, B. E. Levy, D. Thapa, A. L. Oldenburg and C. M. Gallippi, “Blind Source Separation-Based Motion Detector for Imaging Super-Paramagnetic Iron Oxide (SPIO) Particles in Magnetomotive Ultrasound Imaging,” IEEE Transactions on Medical Imaging, vol. 37, no. 10, pp. 2356-2366, Oct. 2018.

[4] M. Evertsson, A. Ramalli, T. Z. Pavan, L. C. Cabrelli, R. Andersson, M. Cinthio, P. Tortoli and T. Jansson, “Towards real-time magnetomotive ultrasound imaging”, 2017 IEEE International Ultrasonics Symposium Proceedings.