Multi-Functional Holographic Ultrasonic Metamaterials Designed by Artificial Intelligence

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Background, Motivation and Objective

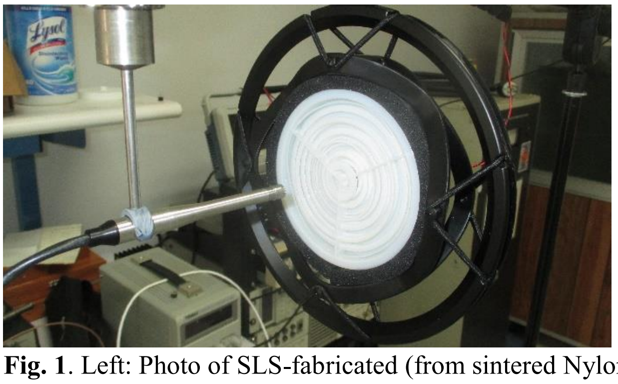
Ultrasonic metamaterials offer enticing and affordable ways to achieve the functionality of active phased arrays in various applications of ultrasound, including medical imaging, acoustic machine vision (including sonar), acoustic communications, contactless manipulation and so on. Coherent beamforming is the enabling ingredient for all of the above applications, and holographic ultrasonic metamaterials (HUM) offer the possibility of achieving it in an attractively thin (as thin as 0.5-1 wavelength of ultrasound) flat layer. Here, we demonstrate that Artificial Intelligence (AI) can completely replace human input into the design of HUMs. Specifically, we use unsupervised Machine Learning (ML) techniques, such as Pareto search, to design metamaterials storing multiple holograms, such as those retrieved using a tunable frequency or selectable spatial content of the excitation ("reconstruction beam").

Statement of Contribution/Methods

For the design methodology, we use COMSOL API for MATLAB to program customized search algorithms in MATLAB scripting language, which make calls to a physical model implemented in COMSOL Multiphysics with Acoustics Module. Search algorithms include both gradient-based and gradient-free methods, with the former using an efficient adjoint method (provided by COMSOL API) to compute the gradient at each training point. Gradient-free methods include discrete-variable methods suitable for binary and multi-nary material architectures. For fabrication of ultrasonic metamaterials and devices, we used several commercially available additive manufacturing techniques, including PolyJet, MultiJet Fusion, and SLS. For ultrasound excitations, we employ various commercially available low-power (1-10 mW) airborne transducers. For measurements, we use Bruel & Kjaer SPL meters (Type 2231 and 4135) with compatible microphones and calibration kits, as well as a standard oscilloscope connected to a microphone probe (B&K).

Results/Discussion

We have proven that unsupervised ML algorithms are capable of designing high-efficiency, fabricable ultrasonic metamaterials with multi-holographic functionality, with zero input from a human operator. Such metamaterials can be used in ultrasound applications requiring dynamic (reconfigurable) beamforming. We have concentrated on the design of focused ultrasound beams, since that is the preferred excitation for the majority of applications, and because a general hologram can be decomposed as a "focal point cloud". Based on the high efficiency of the solutions found (compared to the efficiency of random initial guesses), we conclude that ML algorithms are quite efficient in learning the extremely high-dimensional parameter space from a reasonably small set of "training points". We also conclude that dynamic coherent beamforming is a suitable application for HUMs, particularly when the excitation can be confined to a limited-bandwidth instantaneous spectrum.



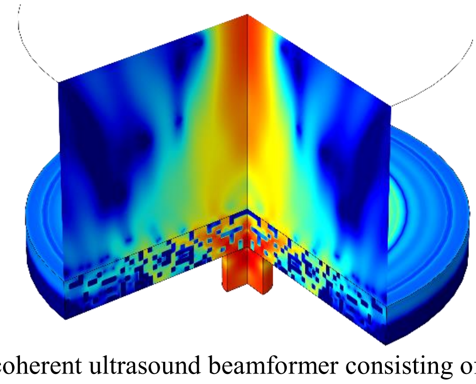


Fig. 1. Left: Photo of SLS-fabricated (from sintered Nylon-12) coherent ultrasound beamformer consisting of a cavity-backed HUM, an acoustic waveguide and a single electroacoustic transducer (not visible). Right: Ultrasound intensity plot of the typical output from an unsupervised ML-inspired search algorithm.