3D Acoustic Imaging Using PMUTs for Synthetic Aperture and NLOS Applications

Shivkumar, Akshay[1,3], Lukhanin, Nikita G[2,3], Muthu Divij[1,3], Behar, Ziv[1,3], Esses, Tofic[1,2,3], Lin, Liwei[2,3]

1. Department of Electrical Engineering & Computer Sciences, University of California, Berkeley, Berkeley, California
2. Department of Mechanical Engineering, University of California, Berkeley, Berkeley, California
3. Berkeley Sensor and Actuator Center, University of California, Berkeley, Berkeley, California

Abstract

Evolution led bats and dolphins to use sound to find food and navigate their environment, but rarely do robots and autonomous vehicles use acoustic sensing. Modern in-air acoustic devices achieve fine distance resolution, but 3D imaging requires dozens of transducers packed in dense arrays, costing far more than their optical counterparts simultaneously losing the power advantages that make ultrasound attractive. We present an eight-channel piezoelectric micromachined ultrasonic transducer (PMUT) array that forms 3D reconstructions of natural scenes via compressed sensing, demonstrating applications towards synthetic aperture and non-line-of-sight imaging applications. Our contributions are: (1) a phase-coherent, MIMO platform for eight-channel PMUT imaging; (2) stationary non-line-of-sight (NLOS) imaging of scenes behind an occluder; (3) a synthetic aperture reconstruction reaching lateral resolution below half a wavelength.

Compressed sensing is the technique that lets us recover a scene using a sparse eight-element array. We can model our problem as an underdetermined linear system: y = Ax + n, where x is the scene, H is the echo each part of the scene would theoretically return for a given set of transmit codes, y is the measured data, and n is the noise. The strategy is to change every element's frequency and firing delay between acquisitions to produce incoherent sampling; therefore, each signal can hit the scene with a different wavefront and add new information. Since natural scenes only contain a few strong reflections, a sparsity-promoting solver can find the x that fits every acquisition via minimizing over $x > 0 : \|y - Hx\|_2^2 + \lambda\|x\|_1$.

Our device on the transmit side consists of a microcontroller that generates eight independent pulse trains and drives each lithium-niobate PMUT independently at 15V with a carrier from 41 to 58 kHz and a delay of up to 200 µs; the PMUTs resonate near 55.8 kHz with quality factors near 13, wide enough to accept the full coded band. Between transmit and receive, a programmable switch matrix connects each element to either path through firmware control. On the receive side, an eight-channel analog front end amplifies the echoes by 54 dB, with the gain chosen so the amplifier defines the noise floor and the chain retains about 75 dB of dynamic range. An 18-bit ADC samples all eight channels simultaneously at 468.8 kSa/s. A full scene is captured as a series of 100 coded acquisitions. We demonstrate this platform with two distinct imaging methods that require no hardware changes. First, we performed stationary NLOS imaging by placing trihedral corner reflectors 1.14m and 1.42m from the array behind an occluder. Second, we formed a synthetic aperture by rotating the array through 24 poses spanning 48° with the same targets, and jointly reconstructed the acquisitions from all poses.

In the NLOS experiments, the array detected the trihedral targets with background-subtracted echoes of 10.6 and 8.5 mV, respectively. These echoes sit about 30 dB above the noise floor in a single acquisition, and the reconstruction localized the targets within −0.4 and +0.9 mm, roughly one-tenth of the 6.1 mm transmitted wavelength. Across the 24 poses, the synthetic aperture spanned an effective 0.67 m and improved lateral resolution 11.3x, from 3.24 cm to 2.87 mm, below half a wavelength. These results show that our platform located targets hidden behind an occluder to a tenth of a wavelength and resolved features finer than half a wavelength, achieving resolution that dense arrays reach only with an order of magnitude more channels. We have thus proven that sparse arrays are capable of high-resolution ultrasound imaging, with the precision now limited by the electronics rather than element count. Additionally, because our platform is reconfigurable via firmware, it provides a common platform for diverse compressed-sensing and learned reconstruction methods. It can give vehicles, drones, and search robots a sense that fog, dust, or darkness cannot take away: the one bats and dolphins have used all along.