Hello

My name is Josiah Smith. I am PhD student at The University of Texas at Dallas pushing the limits of high-resolution radar imaging and deep learning.

Today, I’m going to show you the strides we have been making in near-field MIMO-ISAR millimeter-wave imaging.

In this presentation, I’m going to guide you through the innerworkings of our fully integrated rotational inverse synthetic aperture radar system capable of reconstructing high-fidelity 3-D holographic images.

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Millimeter-wave sensors have recently emerged as a promising solution to a variety of sensing problems in the arenas of security sensing, automotive radar, high-resolution imaging, and many more. Additionally, millimeter-wave radar devices are becoming increasingly affordable due to advancements in system-on-chip RF integrated circuit technology.

The goal of this work is to construct a high resolution mmWave imaging system for holographic 3-D image reconstruction using ISAR techniques and commercially available mmWave radar sensors.

To accomplish this goal, we develop an efficient Fourier-based algorithm for MIMO-ISAR image reconstruction and build a three-dimensional mechanical scanner to synthesize both rectangular and cylindrical apertures.

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I will first overview some background information on the frequency-modulated-continuous-wave or FMCW modulation scheme. An FMCW radar transmits what is called a “chirp” signal. The FMCW chirp signal is a sinusoid that increases in frequency with time and can be modeled by the complex exponential expressed below.

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First, an FMCW chirp is synthesized with the specified parameters. The chirp, m(t), is transmitted from the Tx antenna, reflected from a target in the scene, and received at the Rx antenna as a scaled, time delayed version of the transmitted signal, sigma m(t – tau). The transmitted and received signals are mixed, resulting in the “IF signal” or “beat signal.”

The FMCW beat signal contains high-resolution information about the target scene. The range of the target is embedded in the frequency of the beat signal and can be extracted with a Fourier transform, as shown below.

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Even though the multistatic MIMO array can be approximated by a virtual array of elements at the midpoint of each transceiver pair, the multistatic nature of the MIMO radar introduces phase errors compared to the virtual monostatic array.

However, for small distances between Tx and Rx elements, these errors can be somewhat compensated for using a phase correction known in the literature and expressed below. This multistatic-to-monostatic conversion enables the use of spatially efficient MIMO arrays and computationally efficient monostatic image reconstruction algorithms.

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Let’s consider again the case of the single ideal point reflector. For the monostatic case, the phase profile should be a perfect parabola; however, with a multistatic array, we see discontinuities along the scanned dimension.

After applying the multistatic-to-monostatic conversion, the figure on the right shows the improved phase profile, which appears quite close to the ideal parabola.

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The phase error introduced by the multistatic array produces artifacts in the image reconstruction, if the conversion is not applied. These ghost images can severely degrade the image quality if not properly accounted for.

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Applying the multistatic-to-monostatic conversion, we see a much clearer image, with the multistatic artifacts removed.

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Now, let’s talk about the rotational SAR system.

Our system consists of three main components: a linear vertical scanner, rotator, and FMCW radar. The linear mechanical scanner moves the radar along the *y*-axis up and down. The target is mounted to the rotator, which rotates the target at a constant radial distance (R naught) from the radar scanning plane. The target coordinates are in (x, y, z) and the position of each element in the synthetic aperture are at the points (R naught cosine theta, y’, R naught sine theta) in (x, y, z) space. Lastly, we will use a TI mmWave radar with 2 Tx and 4 Rx channels resulting in an 8-channel colinear multistatic-MIMO virtual array.

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I will briefly discuss the mathematical derivation of the Fourier-based rotational ISAR image reconstruction algorithm. The goal of this algorithm is to recover the target reflectivity function p(x, y, z).

First, the received beat signal can be modeled as the superposition of spherical waves from each point in the target scene weighted by the target reflectivity function, as shown in the equation at the top of the page.

Note the nonlinear phase term due to the radial distance (R) from each element of the synthetic aperture elements to the points of the target. While this integral can easily be inverted, the back-projection approach comes at excessive computational cost.

Instead, we develop a Fourier-based technique by first decomposing the spherical wavefront into the superposition of plane waves using the method of stationary phase.

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Substituting the previous expression into the first equation and simplifying some Fourier relations yields the following equation where P(phi, k r, k y) is the 3D Fourier transform of p(x, y, z) in cylindrical coordinates.

Next, a Fourier transform across y’ is performed on both sides.

Now, it is obvious that the integral on the right is simply a convolution in the phi domain, where we define g(theta, k r) as shown.

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The convolution integral can be written as the following.

Now, P(theta, k r, k y) can be solved using Fourier-convolution relations easily as shown.

Since P(theta, k r, k y) is sampled on a uniform cylindrical grid, it must be interpolated to the k x, k y, k z domain using Stolt interpolation before taking an inverse Fourier transform.

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The full algorithm can be summarized as follows.

First, the multistatic signal is gathered from the radar

The multistatic-to-monostatic conversion is applied yielding a virtual-monostatic approximate

A 2D Fourier transform is performed across the theta and y’ domains

The resulting signal is multiplied with the conjugate of the Fourier transform of the azimuth focusing function g()

After an inverse Fourier transform to complete the deconvolution in the angular spectral domain, the spatial spectral reflectivity function is obtained

Then P(theta, k r, k y) is interpolated to P(k x, k y, k z) using Stolt interpolation.

Finally, a 3D inverse Fourier transform yields the recovered reflectivity function p(x, y, z)

All the Fourier processing can be efficiently computed using the Fast Fourier Transform (or FFT), drastically improving the computational efficiency of this method over the back-projection algorithm. Additionally, the novel pairing of multistatic-to-monostatic conversion with rotational SAR allows us to drastically increase scanning efficiency by using a MIMO array without requiring more computationally taxing multistatic image reconstruction algorithms.

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To validate our proposed MIMO-ISAR algorithm, we simulate some ideal targets.

First, we obtain the point spread function by simulating an ideal point reflector off the rotator axis.

Comparing our algorithm to the gold standard back projection algorithm, which is a matched filter approach. The proposed algorithm performs quite well in terms of image quality, while significantly outperforming the BPA in computational cost.

The ideal point reflector in 3-D, simulated point spread function, and slices along the x-z and x-y planes show the imaging performance of our method.

Next, 9 ideal point reflectors are placed throughout the scene and the echo signal is simulated. Once the proposed reconstruction algorithm is applied, the reconstructed image can be shown to closely resemble the ideal points with minimal distortion.

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Finally, we assemble a fully integrated system with vertical, horizontal, and rotation scanning capabilities allowing for comparison between rectangular SAR and rotational ISAR. The entire scanner is controlled through a custom-built MATLAB graphical user interface that sets up the radar device and controls the scan.

We will proceed to reconstruct high resolution holographic images of the knife shown to the right. Note the notch and serrated edge of the blade, which will be visible in the subsequent images.

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We first compare images from a SISO array of 512 quasi-monostatic vertical elements spaced by a quarter wavelength. To scan at each of the 512 vertical locations, the entire scan took 137 minutes to complete. In contrast, the scan using a MIMO array of the same size took 17 minutes in total. Both the images show a high-quality reconstruction of the knife blade with the notch and serrated edge visible.

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Next, we use the 2-D horizontal and vertical scanning axes to produce 3-D holographic images from a rectangular SAR aperture. We consider multiple cases, 1) the knife blade is parallel with the x-y aperture plane, and 2) the knife blade is perpendicular to the x-y plane. The orientation of the knife with respect to the scanner has substantial implications on the image quality.

The images on the right compare the reconstructed images of the knife blade when the knife is parallel and perpendicular to the scanning plane.

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This demonstrates the high dependence of the image quality on the knife orientation in the rectangular MIMO-SAR regime. While rectangular SAR can reconstruct high-resolution 3-D images of reflective targets, the rotation of the target drastically changes the quality of the resulting image.

By comparison, rotational MIMO-ISAR is rotation-invariant since the target is scanned across a full 360-degree aperture. Further, this results in improved spatial resolution over the rectangular SAR imaging regime.

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In conclusion, we developed a high resolution 3-D near-field imaging system based on low-cost system-on-chip mmWave FMCW radars, a multistatic-to-monostatic conversion, and an efficient Fourier-based rotational ISAR imaging algorithm.

Our experimental results validate our novel MIMO-ISAR 3-D holographic image reconstruction algorithm, demonstrate improved scanning efficiency over SISO systems, while maintaining high-resolution image quality, and establish the rotational-invariance advantage of rotational ISAR over rectangular SAR.

Proved by simulation and empirical measurement, our fully integrated system allows for efficient near-field MIMO-ISAR mmWave imaging offering an elegant solution to many near-field imaging and sensing problems.

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Thank you for attending this presentation

My name is Josiah Smith and I look forward to answering your questions shortly