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Original Article Title: “Efficient 3-D Near-Field MIMO-SAR Imaging for Irregular Scanning Geometries”

To: IEEE Access Editor

Re: Response to reviewers

Dear Dr. Gerardo Di Martino,

Thank you for allowing a resubmission of our manuscript, with an opportunity to address the reviewers’ comments.

We are uploading (a) our point-by-point response to the comments (below) (response to reviewers), (b) an updated manuscript with yellow highlighting indicating changes, and (c) a clean updated manuscript without highlights (PDF main document).

Best regards,

J. W. Smith and M. Torlak

Reviewer #1, Concern #1: The authors said the proposed method 'enables such mobile and internet of things (IoT) applications through efficient image reconstruction.' However, the 5G and IoT signals are usually modulated into an orthogonal frequency division multiplexing (OFDM) form, while the experiments reveal that the LFM signals are employed in this manuscript. Can you explain this?

Author response: The authors are grateful for the comments and suggestions of Reviewer #1. Because to the diversity of modulation schemes, the signal model presented in Section II-C provides a generalized model to accommodate both OFDM and LFM radars, both of which are found in smartphone and IoT hardware. The reviewer is correct that it is common practice for 5G and IoT signaling to employ orthogonal frequency division multiplexing (OFDM) as opposed to linear frequency modulation (LFM) or frequency-modulated continuous wave (FMCW), which is common in automotive radar. Furthermore, the proposed algorithm discussed in Sections II and III is applicable to both OFDM and LFM signaling schemes, as clarified in the updated version of the manuscript. In addition, we have included further references for the reader detailing OFDM radar for ranging and synthetic aperture (SAR) imaging. On the other hand, FMCW (LFM) modulation has been employed previously for smartphone applications to achieve radar sensing in the Google Pixel 4 with Google Soli radar, and is commonly used for sensing exclusively in IoT applications. Prior work on smartphone SAR and similar applications employed a purely LFM, stepped frequency signal model [10]-[13]. Therefore, the signal model in Section II is generalized for any UWB modulation scheme, and the proposed algorithm is applicable to both LFM and OFDM modulation schemes.

We appreciate the reviewer's suggestion and have made changes to provide a clear explanation for the audience.

Author action: We updated the manuscript by the following actions:

1) In Section II-C, we added the following sentence to clarify the validity of the generalized signal model for common ultrawideband (UWB) modulation schemes.

   "The frequency-domain model of the received signal (9) is valid for any UWB radar signaling scheme, including frequency-modulated continuous-wave (FMCW), phase-modulated continuous wave (PMCW), and orthogonal frequency-division multiplexing (OFDM), which is commonly employed in 5G and IoT applications [35]. Furthermore, prior research on freehand imaging and similar IoT applications has employed a purely stepped-frequency FMCW signal model [10]-[13]. Similarly, Google Pixel 4 utilizes a Google Soli 60 GHz mmWave FMCW radar for sensing [8]."

2) In Section IV, we clarified the choice of an FMCW radar and the efficacy of the proposed algorithm for both OFDM and FMCW radar signaling by adding the following.

   "Although 5G and IoT applications commonly employ an OFDM modulation scheme, the TI radar employed for the following experiments utilizes FMCW signaling. However, FMCW radar has been utilized for smartphone applications, notably the Google Pixel 4, which is equipped with a Google Soli FMCW radar [8]. The proposed range migration-based algorithm is applicable to both OFDM and FMCW radars; hence, the results discussed in the following section are relevant for a wide array of 5G, IoT, smartphone, and automotive applications [39]."

Reviewer #1, Concern #2: It seems that the Tx and Rx are fixed in the board and have the same movement state, since the TI AWR1443BOOST is used in the experiments. Does it meet the requirements for irregular sampling in real scene?

Author response: The authors appreciate this comment from the reviewer. The reviewer is correct that the transmit (Tx) and receive (Rx) elements were fixed on the radar board in the experiments. However, the number of elements on the board is small, such that the radar is suitable for a smartphone or an IoT application. However, challenge is to synthetically create a uniform aperture geometry. Existing techniques for image reconstruction with non-cooperative near-field scanning geometries are computationally burdensome and infeasible for mobile applications. The irregular scanning geometry investigated in this manuscript, referred to as multi-planar multistatic, is an extension of the common planar MIMO-SAR scanning mode. In planar MIMO-SAR, a multistatic radar platform is scanned across a planar aperture, which implies the Tx and Rx elements are fixed to the board and spatially translated as the radar is scanned across the planar track. The algorithm proposed in our manuscript offers an efficient solution to the MIMO-SAR case, such that the planar assumption does not hold. For applications such as freehand smartphone imaging or automotive SAR, the MIMO radar is scanned across space, but the planar array assumption is invalid. For the multi-planar MIMO-SAR scanning mode described in Section II-A and shown in Fig. 1, the Tx and Rx are fixed on the radar and the entire radar platform is moved throughout space in an irregular scanning pattern. Hence, the TI AWR1443BOOST used in the experiments meets the irregular sampling conditions investigated in this manuscript.

To provide further clarity, we have added additional details to Section II-A explaining the multi-planar MIMO-SAR operation and its potential applications.

Author action: We have updated the manuscript by adding the following paragraph to Section II-A:

> "Compared with planar MIMO-SAR, which requires a multistatic MIMO array to be scanned across a planar track [17], [20], [31], multi-planar MIMO-SAR allows the multistatic array to be scanned across 3-D space. For freehand imaging or automotive SAR, a MIMO array is fixed to a smartphone or vehicle, respectively, and is moved throughout space, generating a multi-planar MIMO-SAR irregular aperture. As shown in Fig. 1, because the multistatic array is scanned in an irregular pattern spanning multiple *z*-planes, the locations of the transmit (Tx) and receive (Rx) elements are spatially translated by the movement of the MIMO array. The analyses in the subsequent sections present an efficient solution to irregular MIMO-SAR imaging, such that the position of the radar is known throughout the scan and the planar array assumption does not hold. This scenario is common for many of the aforementioned applications and necessitates both irregular scanning geometries and efficient image recovery."

Reviewer #1, Concern #3: The sampling rates, i.e., pulse repetition frequency (PRF) and sampling rate in base band, should be analyzed to avoid the undersampled case.

Author response: The authors agree with the reviewer's comment and have included more detailed analyses of the spatial and temporal sampling rates to avoid undersampling. The spatial and sampling, dictated by the pulse petition frequency (PRF), and baseband sampling rate are both relevant factors in system design and implementation and have been explored more thoroughly in the updated manuscript.

Author action: We have updated the manuscript by making the highlighted change to the following excerpt from Section III:

> "Sampling considerations for image reconstruction remain identical to those in analyses elsewhere [17], [29], after the multi-planar compensation algorithm. Baseband frequency sampling criteria can be determined by the maximum range for a given application. As given in [38], the maximum frequency sampling interval is given by $\Delta_f < c/(2R_{\max})$, where $R_{\max}$ is the maximum target range. Although spatial sampling criteria are not guaranteed for irregular SAR scanning, if the relationship between the capture rate of the radar and the velocity of the radar platform is tuned appropriately during system design, undersampling artifacts are typically minimal [10]-[13]. To avoid spatial undersampling, the lower bound of the pulse repetition frequency (PRF) can be computed using PRF $> 4v_{\max}/\lambda_c$, where $v_{\max}$ is the maximum velocity for a certain application. For example, assuming that the maximum velocity of the human hand for a freehand SAR is 1 m/s and a center frequency of 79 GHz, the lower bound of the PRF is approximately 1.06 kHz. It is important to note that the number

of captures increases proportionally to the PRF; hence, at high velocities, a large number of samples are captured. The computational performance of traditional techniques that employ the BPA degrades substantially when many samples are captured. On the other hand, the signal-to-noise ratio can be improved by increasing the number of samples at the cost of an increased computational burden. Hence, an efficient algorithm for multi-planar MIMO-SAR imaging is required to enable many such technologies."

Reviewer #1, Concern #4: It is a good work to analysis the 3D resolutions in Eq.(17). Why not validate these resolutions in the experiments part?

Author response: This comment, in addition to Reviewer #2 concern #3, is an excellent suggestion to bolster the robustness of this study. We have revised the manuscript to include an investigation of the spatial resolution and the impact of the extent of sampling irregularity on the imaging resolution. The resolution of the proposed algorithm is compared with that of the ideal, planar RMA image reconstruction algorithm with varying degrees of array perturbation.

Author action: We have updated the manuscript by including a thorough study of the impact of sampling irregularity on image resolution by considering the point spread function (PSF) for several non-cooperative scanning geometries. Each PSF is simulated with a different value for $\Delta_z^{\max} \triangleq \max|d_\ell^z|$, the maximum distance between the reference plane, Z_0, and the samples, as defined in Section II-B. The simulated PSFs are compared with the PSF from an ideal planar scenario using the traditional RMA. As the value of $\Delta_z^{\max}$ increases and the synthetic array becomes increasingly nonplanar, the resolution of the main lobe along the *y*- and *z*-directions degrades marginally, and inferior sidelobe suppression is observed. However, even with significant perturbations in the array geometry, the resolution of the proposed algorithm is quite similar resolution to that of the RMA under ideal conditions. Prior work on freehand smartphone imaging system design and implementation assumed deviations on the order of several centimeters [7]. The results are detailed in the updated manuscript in Section V-A, and are presented in Fig. 5. Further details and explanations are provided under Reviewer #2, Concern #3.

Reviewer #1, Concern #5: It appears that the RM algorithm is adopted in case of 3D non-cooperative SAR imaging, in this manuscript. Can you explain the difference between traditional RM algorithm and your proposed RM algorithm?

Author response: The authors appreciate this comment from Reviewer #1. The proposed range migration (RM) algorithm is an adapted version of the traditional RM algorithm for 3-D non-cooperative MIMO-SAR in the near-field. The proposed algorithm efficiently solves both the multi-planar (irregular) sampling problem and the MIMO-SAR problem by aligning the multi-planar multistatic data to virtual planar monostatic data for efficient image reconstruction. The multi-planar multistatic to planar monostatic projection is the main difference between the proposed RM algorithm and the conventional RM algorithm. This crucial step compensates for both the sampling irregularities and multistatic MIMO effects simultaneously while reducing dimensionality and computational complexity. The manuscript has been updated to explicitly describe the novelty of the proposed algorithm.

Author action: We updated the manuscript by the following actions:

1) In Section I, we have clarified the distinction between the traditional RMA and our proposed algorithm by including the following highlighted portion to this paragraph.

"In this article, we propose a novel image reconstruction technique for efficient near-field imaging with irregular scanning geometries, such as those present in freehand imaging, UAV SAR, or automotive scenarios. We examine the system and signal models for UWB MIMO-SAR and develop a multi-planar multistatic approach to mathematically decompose the irregularly sampled synthetic array such that an equivalent virtual planar monostatic array can be constructed. This technique is the first to extend the range migration algorithm (RMA) such that non-cooperative SAR scanning and multistatic effects are simultaneously mitigated. The analysis in the subsequent sections provides a novel framework for decomposing irregular SAR scenarios and efficiently projecting irregular MIMO-SAR samples to a virtual planar monostatic equivalent. The proposed algorithm is validated through simulation and experimentation, demonstrating its robustness to arbitrary scanning patterns and low computational complexity. A thorough study of the relationship between array irregularity and image resolution of the proposed algorithm. The proposed technique demonstrates high-fidelity focusing comparable to the traditional planar RMA, even under array perturbation on the order of 10s of wavelengths. Our solution enables the development of emerging technologies that require non-ideal SAR scanning geometries, MIMO multistatic radar, and efficient image reconstruction."

2) In Section III, we have added the following details to further address the novelty of the algorithm proposed in this study.

"The key difference between the traditional RMA and the proposed algorithm is the alignment of the multi-planar multistatic (MIMO-SAR) data to virtual planar monostatic data. This crucial step compensates for both the sampling irregularities and multistatic MIMO effects simultaneously, while significantly reducing the dimensionality, from 6-D $(x_T, x_R, y_T, y_R, z_\ell, f)$ to 3-D (x', y', f), and subsequently the computational complexity."

3) In Section VI, we have included the highlighted portion below to provide a thorough discussion of the novel extension of our technique to the conventional RMA.

"In this article, we presented a novel approach for high-resolution, efficient 3-D near-field SAR imaging for irregular scanning geometries. We proposed a multi-planar multistatic framework applicable to a diverse set of applications, including freehand imaging, UAV SAR, and automotive imaging. A novel algorithm is proposed to efficiently compensate for irregularly sampled multi-planar multistatic data to equivalent planar monostatic mmWave radar data. Our technique extends the traditional RMA by presenting an algorithm for efficiently aligning multi-planar multistatic data to a virtual planar monostatic scenario. By projecting the data onto a virtual planar monostatic equivalent array, this method extends the RMA to account for both irregular scanning and MIMO-SAR effects, resulting in high-fidelity focusing. The proposed algorithm is valid for common radar signaling techniques in 5G, IoT, smartphones, and automotive applications. The simulation results demonstrate the robustness of our approach in the presence of significant spatial deviation among the samples along the *z*-direction. Furthermore, we empirically validated the proposed algorithm by using a custom prototype to capture multi-planar multistatic data for several concealed and obscured scenarios. In both simulation and experimental studies, our algorithm achieves efficient image reconstruction matching the focusing quality of existing techniques while reducing computational complexity by a considerable margin."

Reviewer #2, Concern #1: The authors should include the number of considered samples used to compute each of the electromagnetic images.

Author response: The authors would like to thank Reviewer #2 for their comments and concerns. We agree with the reviewer's suggestion and have updated the manuscript to include the number of samples used to compute each electromagnetic (EM) image.

Author action: We have updated the manuscript to include the number of samples for both the simulated and empirical EM images in Section V.

Reviewer #2, Concern #2: The size of the images of Figures 11b, 11d, 12b and 12d could be increased for a better readability.

Author response: The reviewer makes an excellent suggestion that the clarity and readability of Figs. 11b, 11d, 12b, and 12d can be improved. We have merged Figs. 11 and 12 into a single figure covering both columns and have increased the size of the 3-D figures mentioned by the reviewer.

Author action: We updated the manuscript by combining Figs. 11 and 12 into a single figure and increasing the size of the figures as per the reviewer's suggestion.

Reviewer #2, Concern #3: How far in the z direction can the samples be from the plane Z0? It seems that if sampling is smooth samples can be acquired at a large distance from the plane Z0.

Author response: The authors appreciate the reviewer's suggestion and agree that the manuscript can be improved by including a detailed study into the resolution limitations of the proposed algorithm with increasingly irregular arrays. The authors have modified the manuscript to include an investigation of the impact of the distance between the samples, z_ℓ, and the Z_0 plane on the image resolution. Section V-A and Fig. 5 provide the results and discussion of the resolution of the proposed algorithm as the array is degraded by perturbations and becomes increasingly non-linear or non-planar. The proposed algorithm achieves nearly identical main-lobe resolution at the cost of increased sidelobes as the array geometry becomes increasingly non-ideal.

Author action: We updated the manuscript by adding a paragraph to Section V-A and a figure detailing a study of the spatial resolution of our algorithm compared to the resolution of the planar RMA in an ideal planar scanning scenario. Fig. 5 shows the range and cross-range point spread function (PSF) using the proposed algorithm with various irregular arrays of increasing $\Delta_z^{\max} \triangleq \max|d_\ell^z|$, the maximum value of d_ℓ^z, the distance between the samples and the reference plane Z_0. The PSF results demonstrate the focusing performance of the proposed algorithm compared to the traditional RMA and the main lobe beamwidth as $\Delta_z^{\max}$ increases, or the samples are taken farther from the reference plane. The system designed and implemented in [7] for freehand smartphone imaging assumes deviations on the order of several centimeters, and our algorithm achieves comparable resolution to that of the ideal planar case with much larger values of $\Delta_z^{\max}$. The results in Fig. 5 provide further insights into the efficacy and limitations of the proposed algorithm. Further details and explanations are provided under Reviewer #1, Concern #4.

Reviewer #2, Concern #4: In column 1 of page 4 it seems that "is" is missing after "instantaneous wavenumber".

Author response: The authors appreciate the careful reading by the reviewer and concur that this portion of the manuscript must be improved. We implemented the suggested change in the revised manuscript.

Author action: We have updated the manuscript by incorporating the change suggested by the reviewer in the following sentence:

> "... where $k = 2\pi f/c$ is the instantaneous wavenumber and $P(f)$ is the Fourier transform of $p(t)$."

Reviewer #2, Concern #5: Can you include a link to a preprint/pre-release of [22]?

Author response: The authors will gladly share the preprint copy of the reference requested by the reviewer, [22] in the previous manuscript and [24] in the updated manuscript. The preprint document is attached as "Supplemental Material not for Review and not for Publication" in the new submission.

Author action: We have included the requested preprint document as "Supplemental Material not for Review and not for Publication" in the new submission.
