Inverse Synthetic Aperture Radar Imaging at 580 GHz

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***Abstract*—We have demonstrated sub-centimeter resolution Inverse Synthetic Aperture Radar (ISAR) imaging using a 580 GHz, frequency modulated continuous wave (FMCW) radar. This ISAR technique uses pulse compression possible with the FMCW waveform to achieve resolution in range, and exploits rotation of the target to achieve resolution in cross-range. The technique relies on the illumination of the entire target rather than scanning with a narrow beam, which permits larger ranges or smaller apertures than real-aperture approaches. The data collection time required for an ISAR image is less than the collection time with a mechanically scanned beam, which is an advantage in highly dynamic scenarios. The ISAR algorithms presented here accommodate radial motion of the target and non-uniform rotation rates. Thus, the algorithms are suitable for applications where the target motion is not under the control of the observer. These algorithms enhance submillimeter-wave radar technology for surveillance and concealed-object detection.**

I. Introduction And Background

SUBMILLIMETER-BAND radar is a promising technology for the detection and imaging of objects concealed under clothing. Most clothing is reasonably transmissive at these frequencies, and currently achievable power and apertures can provide standoff ranges of 10-100 meters. In addition, Terahertz radiation is non-ionizing, making these systems safe for both the operator and individuals under surveillance.

Detection of metal objects under clothing has been demonstrated with an all solid-state coherent radar operating at 576-589 GHz [1]. The radar uses linear swept frequency (FMCW) across a bandwidth of nearly 30 GHz to achieve a range resolution of about 0.5 cm. Using a 40-cm diameter reflector, a THz beam can be focused on a 0.6 cm spot at a distance of 4 meters. Using this configuration the system is able to form a 3-dimensionsal image by scanning the beam in two dimensions over the target area. Figure-1 shows an image produced with this technique. Figure-2 shows the target configuration: The letters “ISAR” cut from sand paper.

II. Theory

Inverse Synthetic Aperture Radar (ISAR) imaging is a signal processing technique commonly used at microwave frequencies for the identification and analysis of targets such as ships and aircraft [2][3]. A two-dimensional ISAR image presents radar reflectivity of a target as a function of range and cross-range from the radar. The range resolution is a function of the bandwidth of the transmitted pulse; the wide bandwidth required can be achieved using a short duration pulse or by modulating the transmitted signal. Linear Frequency Modulation (LFM) is a common modulation approach. The process of demodulating a received signal to obtain range resolution is called pulse compression.

The cross-range resolution in an ISAR image is obtained by processing the data from multiple successive, phase-coherent pulses. This is a form of Doppler processing; changes in the phase of the reflected radar signal that result from target motion are detected. In order for two points on a target to be resolved in Doppler, their change in range over the observation time must differ by at least one half of a wavelength. In the case of a rigid body rotating around an axis perpendicular to the radar line-of-sight, the Doppler shift of a point on the body is proportional to its cross-range distance from the axis of rotation. If the rotation rate is known, the cross-range position can be calculated from the Doppler frequency.

Translational motion of the target towards or away from the radar does not provide useful information for image resolution. This motion is a nuisance parameter that must be estimated and removed prior image formation in process is known as motion compensation. Motion compensation is accomplished by estimating the radial velocity from estimates of the Doppler centroid. [4]

Optimum linear processing requires the formation of a matched filter for each image point. Most ISAR algorithms use the Fast Fourier Transform (FFT) to form multiple cross-range points at once. The FFT does not provide an exact solution, however, because points on a rotating target will have radial velocity and range that change as a function of rotation angle. This migration of a point target between range and Doppler bins results in blurring of the image. To mitigate the blurring effect, the Fourier Transform can be augmented with various interpolation or reformatting approaches. Creation of the matched filter requires knowledge of the target’s range and rotation angle at the time each returned pulse is collected. For many practical applications, these dynamic parameters are not known a priori, and must be estimated from the data. This can be accomplished iteratively by hypothesizing the rotational parameters, forming the image, and then estimating its focal quality; the drawback of the approach, however, is that it is computationally expensive [5].

We have developed an alternative approach that estimates the rotational parameters as part of a single-pass image formation process [6]. It starts with a series of compressed, motion-compensated pulses. Each pulse is a sequence of complex samples of the target’s reflectivity as a function of range relative to the target’s center of rotation. The data can be formed into a 2-dimensional array with range in one

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dimension and time in the other. The time dimension is divided into short overlapping segments to which the Fourier Transform is applied. This produces a stack of sub-images that consist of range bins on one axis and coarse-Doppler bins on the other. The FFT length is chosen such that point targets do not migrate out of a sub-image bin.

Point targets still migrate over the sequence of sub-images. Our algorithm detects targets in the sub-image stack and tracks their motion, which can be interpreted as an uncompensated acceleration [7]. The acceleration is modeled as a linear function of range and Doppler frequency. The coefficients of this model are estimated as the linear-least-squares solution for the set of detected point targets. Once this acceleration field has been estimated, it is used to determine a mapping from the sub-image stack to a new 3-D array where the migration of the point targets has been removed. Next, Fourier transforms are performed along the remaining time dimension of the array, producing fine-Doppler resolution. The fine-Doppler segments are blended together to form a final range-Doppler image.

This approach is very robust to target motion when there are detectable targets in the sub-image stack. Additional focus improvements can be achieved through application of the Phase-Gradient Auto-focus (PGA) algorithm [8] to the output image to remove residual radial motion.

III. Results

ISAR imaging requires that an entire object be illuminated with a plane wave. To illuminate the entire object, the existing 40-cm reflector was replaced with a smaller one. At the radar wavelength, a change in angle of 1.5 degrees results in 1-cm cross-range resolution. The target was rotated around an axis near the right side of Figure-2, at a rate of 0.4 deg/sec and pulses were collected every .025 sec. Figure-3 shows the ISAR image produced by processing 512 pulses. In this image, the y-axis represents distance from the radar, and the x-axis represents Doppler frequency. The Doppler is proportional to cross-range distance (based on the angle change over the data collection period).

IV. Conclusions

The combination of sub-millimeter wavelength and ISAR processing shows promise for the development of cost-effective surveillance and concealed-object detection systems. The sub-millimeter wavelength provides clothing penetration, potential high range resolution, and sensitivity to very small amounts of motion. ISAR processing techniques provides two-dimensional imaging without the cost and complexity of multi-sensor arrays and real-aperture beam scanning.

Figure-1 Real-aperture THz Radar image

Figure-2 Optical image of target

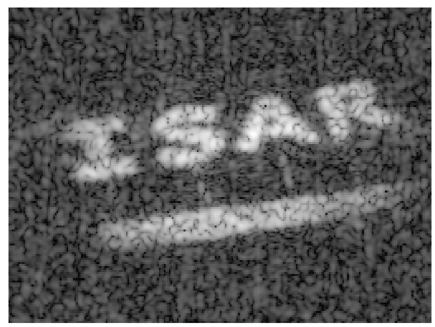

Figure-3 THz ISAR image

References

[1] K.B. Cooper, R.J. Dengler, G. Chattopadhyay, E. Schlecht, J. Gill, A.Skalare, I. Mehdi, and P.H. Siegel, “A High-Resolution Imaging Radar at 580 GHz”, *IEEE Microwave Wireless Components Letters*, vol. 18, no. 1, pp64-66, Jan. 2008.

[2] M Skolnik, ed., *The Radar Handbook*,. McGraw Hill, 2008, p 5.31.

[3] D.R.Wehner, High *Resolution Radar Imaging*, Artech House, 1995

[4] J.A.Trischman, “Real-time motion compensation algorithms for ISAR imaging of aircraft,” *Proceedings of SPIE*, W. Miceli, Vol. 2845, pp 110-119, Denver, 1996.

[5] R.P.Bocker, S.A.Jones, “*ISAR motion compensation using burst derivative as a focal quality indicator*,” IJIT, Vol 4, pp.285-297, 1992.

[6] J.R.Bennett, “Motion in ISAR focusing,” *Proceedings of SPIE*, W. Miceli, Vol. 3161, pp 40-47, San Diego, 1997

[7] K.A.Melendez, J.R.Bennett, “ISAR target parameter estimation with application for automatic target recognition,” *Proceedings of SPIE*, W. Miceli, Vol. 3462, pp 2-13, San Diego, 1998.

[8] D.E.Wahl, D.C.Eichel, C.V.Ghiglia, “*Phase Gradient Autofocus – a robust tool for high resolution SAR phase correction*,” IEEE AES-30, No. 3, July 1994.