An All-COTS Automotive Radar for SAR Imaging and Target Classification

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Abstract—In this concept paper, a radar concept developed by a team from the University of Oklahoma using a fully COTS FMCW automotive radar module produced by Texas Instruments is presented. The radar system is designed to perform synthetic aperture radar (SAR) as a method for locating targets in three-dimensional space. The basics of FMCW processing are given, along with the fundamentals of SAR processing. A control system and mechanical positioner are formulated for the purpose of positioning the radar with precision. Additionally, the basics of deep-learning networks for radar target classification are discussed.

I. INTRODUCTION

As vehicles become more and more sophisticated, employing features such as blind-spot detection (BSD), lane-change assist (LCA), adaptive cruise control (ACC), and other autonomous functions, sensors monitoring the road for vehicles and other obstacles must become more and more robust [1]. Because sensing and classification of these obstacles potentially requires fine sensing resolution, a large radar signal bandwidth is desirable. In lower frequency RF bands, the spectrum is becoming more and more congested as new radar and communications devices compete for more bandwidth. This has motivated the automotive radar industry to jump to higher frequency bands, starting with a narrow ISM band at 24 GHz and more recently a 4 GHz band from 77-81 GHz. This band is ideal for automotive radar because the relatively short scale of distance required for target sensing negates the path loss and attenuation penalty of moving to higher frequency while allowing for wideband signals that can give range resolutions as precise as 4 cm.

For similar reasons, automotive radar operating in the 77-81 GHz band is also ideal for the Radar2020 Radar Challenge. Because the scene size will be small, path loss and attenuation of the signal will not reduce radar performance nearly as much as a large scene size would. The ability to operate with a wide bandwidth will also allow targets to be determined in location with much finer precision, and targets closer together have a higher likelihood of being distinguished from one another. Additionally, the wideband automotive radar remains compliant with FCC Chapter 15 [2].

In this concept paper, the radar overview produced by the University of Oklahoma team at the Advanced Radar Research Center is provided. A COTS automotive radar module has been selected for use in this competition (Sections II and III). The radar will be used for 2D and 3D image formation using synthetic aperture radar (SAR) with assistance from a mechanical positioner and control system used to form the synthetic aperture (Sections IV and V). The radar data can also be co-processed in a ground-moving target indication (GMTI) algorithm to obtain information about the location and velocity of moving targets within the scene (Section IV). Finally, using a deep-learning method for target classification being researched at the University of Oklahoma, the radar data will be processed to attempt to classify the targets as either spherical or corner reflectors (Section VI).

II. FMCW OPERATION

The University of Oklahoma will be using a Frequency Modulated Continuous Wave (FMCW) radar system for the IEEE Radar 2020 Challenge. FMCW was chosen to ensure the system will be able to operate and collect useful data in the close proximity scene since it is capable of collecting range and doppler information without a blind range due to the nature of its continuous operation.

A Linear Frequency Modulated (LFM) waveform is used to transmit a chirp over the desired bandwidth. This LFM waveform, at bandpass, is given by

\[ x(t) = \exp\left(j\pi\beta t^2\right) \exp(j\Omega(t-t_b)). \]  

where \( \beta \) is the bandwidth of the signal, \( t \) is the fast-time axis, \( \tau \) is the pulswidth of the transmitted pulse, and \( \Omega \) is the carrier frequency. The received signal is a time delayed version of the transmitted waveform, arriving at a later time of \( t_0 \). The received signal, given by

\[ \ddot{x}(t) = \rho \exp\left(j\pi\beta t^2\right) \exp(j\Omega(t-t_b)). \]  

where \( \rho \) is the reflectivity of the scatterer, is then mixed with a reference signal, typically chosen to be the signal that would be received from some reference range, received at time \( t_0 \). The resulting signal is said to be “deramped” and is given by

\[ y(t) = \rho \exp\left(-j\frac{4\pi R_b}{\lambda}\right) \exp\left(-2j\pi\frac{\beta}{\tau}(t-t_0)\right) \exp\left(j\pi\frac{\beta}{\tau}(\delta t_b)^2\right). \]  

Here, \( \lambda \) is the wavelength of the carrier, \( R_b \) is the range to the return received at \( t_b \), and \( \delta t_b \) is the time difference between the target and reference range. The second exponential in equation 3 represents a constant frequency complex sinusoid.
with frequency dependent on the target’s distance from the reference. This range-dependent beat frequency can be used to create a range profile by taking a Fourier Transform of the received signal. A thorough derivation of stretch processing is given in [3]. Fig. 1 shows the received signals from a target at the near edge of the scene and one at the far edge of the scene. These two signals are mixed with the reference signal, in black, which downconverts them to baseband where they have a constant frequency related to their range. In order to gather information on the Doppler shift of a target, several pulses will be transmitted and processed using a discrete Fourier Transform (DFT).

### III. TI AUTOMOTIVE RADAR MODULE

The hardware we are using is a commercially available automotive FMCW radar system (Texas Instruments AWR1642) packaged in its evaluation module (AWR1642BOOST). The system is small enough to be easily mounted to a linear actuator system that will move the radar to create the synthetic aperture required for SAR processing (see Section IV).

The AWR1642, shown in Fig. 2, is an integrated single-chip FMCW radar sensor capable of operation in the 76- to 81-GHz band. The AWR1642 was chosen due to its low-power consumption, small form factor, and high bandwidth. It integrates the DSP subsystem, which contains TI’s high-performance C674x DSP for the Radar Signal processing. The device includes an ARM R4F-based processor subsystem, which allows radio configuration, control, and calibration. Custom programming model changes can enable a wide variety of sensor implementation with the possibility of dynamic reconfiguration for implementing a multimode sensor. The radar module is equipped with 2 transmit channels and a 4 receive channels in a linear array. Having multiple receive channels allows for digital beamforming, as well as the implementation of several gmti techniques.

To interface with the AWR1642, the Texas Instruments DCA1000EVM capture card will be used. The capture card enables streaming of raw ADC data over an ethernet connection to a PC for post-processing. The design of this capture card is based on the Lattice FPGA LF85UM85F-8BG381I with DDR3L. The raw ADC data is stored to the computer as a .bin file, which is then parsed and post-processed in MATLAB.

### IV. SAR IMAGING AND MOVING TARGET DETECTION

A radar’s range-resolution is governed by the bandwidth of the transmit waveform, whereas the angular resolution is limited by the physical size of the antenna aperture. Typically in airborne radar applications, hardware size is limited by the physical space allotted to the radar system. This limitation gives rise to the use of synthetic aperture radar, which uses the inherent motion of the airborne platform to create a synthetic array by sending pulses over the duration of some coherent processing interval (CPI). The pulsed data can then be processed using an imaging algorithms such as Backprojection or Polar Format Algorithm [4][5], giving rise to high-fidelity images of the scene of interest. In order for the algorithms to coherently process data, precise knowledge of the antenna location is required. For airborne applications, this requires the use of high quality IMUs and GPSs. For a ground-based system imaging a small volume, the platform can be affixed to a linear actuator, driven by high quality motors with some method of tracking precise position (such as encoders or a step motor driver) to deliver the precision needed for coherent processing. Yanik and Torlak [6] have shown the feasibility of using an automotive radar module for high resolution imaging of concealed targets using SAR processing. To complement high resolution imaging of the scene, moving target indication will be performed to detect moving targets within the scene.

SAR processing will be used to achieve high cross-range resolution to complement the radar’s high range-resolution. Range-resolution for an ILFM waveform is given by

\[ \Delta_R = \frac{c}{2\beta} \]  

where \( c \) is the speed of light and \( \beta \) is the bandwidth of the waveform. Based on this equation, the automotive radar module has a maximum range-resolution of roughly 3.75 centimeters. Cross-range resolution for a SAR system is given by

\[ \Delta_{CR} = \frac{\lambda R}{2D} \]

where \( \lambda \) is the wavelength of the carrier, \( R \) is the range to the scatterer of interest, and \( D \) is the length of the synthetic
aperture. A synthetic aperture length of one meter will result in a cross-range resolution of roughly 3.8 centimeters at the scenes furthest point of 20 meters, resulting in square pixels. Due to the range dependence in equation 5, cross-range resolution is spatially variant, meaning that the resolution closer to the radar will be significantly smaller than 3.8 centimeters. In traditional SAR systems, the range to the scene center is large enough that the spatial variation can be ignored, but here, some consideration must be made on how to handle this issue. Using the radar module affixed to a single linear actuator will result in high range-resolution and high resolution in the horizontal plane of the target area, but the vertical plane will have low resolution. If the radar module were positioned such that the array were oriented vertically, beamforming could be performed to achieve higher resolution in the vertical dimension, but this resolution would still be significantly worse than the horizontal dimension as the beamwidth of the patch array on-board the radar is too large. As Yanik and Torlak demonstrated, the use of two orthogonal linear actuators provides high resolution in both cross-range dimensions. Using multiple actuators, we will be able to achieve approximately equal resolution in all three dimensions, allowing for a volumetric image of the scene to be created.

One major advantage of the automotive radar’s built-in antenna array is the ability to perform one of several different GMTI algorithms. GMTI techniques work by filtering out clutter, leaving returns that only contain a signal from moving targets. The two GMTI techniques of interest for this project are the displaced phase center antenna (DPCA) technique and along-track SAR interferometry (AT-InSAR) [3][7]. DPCA and AT-InSAR require accurate knowledge of antenna locations on each pulse, as well as the ability to send out each pulse at exactly the desired location on each pulse. DPCA and AT-InSAR both require that the physical array is aligned along the direction of motion, so the scheme for transmitting pulses will have to be chosen such that this is satisfied while still moving in two dimensions. Implementation of these techniques will also be limited by the control system’s ability to provide the necessary precision and accuracy.

V. MECHANICAL POSITIONING AND CONTROL SYSTEM

As discussed in Section IV, focusing of a SAR image requires that the position of the radar be known with an accuracy on the order of the wavelength of the transmit frequency at every pulse. The transmit frequency of the TI automotive radar is 77+ GHz, resulting in a wavelength of less than 4 mm. Consequently, the position of the radar must be known at each pulse with an accuracy of less than 1 mm. In many systems, the position of the radar can be determined using an inertial measurement unit (IMU). However, even with expensive, state-of-the-art IMUs, positional accuracy is dependent on another "ground truth" measurement (usually GPS) to correct for gyroscope and accelerometer biases, and the position measurements made by the IMU even with GPS correction are typically only accurate on the centimeter order of magnitude [8].
Kalman Filter is a state-space control algorithm that develops the maximum likelihood estimate of a system state (in this case, the position of the radar in a 2-D space) using possibly inaccurate sensors and a system that slightly deviates from a mathematical model. The mathematics of the Kalman Filter are developed extensively in [9].

The digital control of the stepper motors and the data collection from an IMU, if it is required, will be performed by a high-performance microcontroller unit (MCU) such as the TI LAUNCHPAD.

VI. DEEP LEARNING TARGET RECOGNITION

In this project, Convolutional Neural Networks (CNNs) will be employed to classify targets. Unlike traditional programming that requires a known algorithm developed by a human, machine learning develops a model by training itself using datasets that consist of input data and pre-determined output labels. Once trained, the model is able to determine the output label autonomously using only input data, or an “image”.

CNNs are one of the machine learning methods that are widely employed in image classification. In general, the CNNs model is the combination of convolutional layers, pooling layers, an activation function, and fully-connected layers. The convolutional layer is utilized to extract the features, the pooling layer is employed to down-sample the data, the activation function applies a threshold to the data, and the fully-connected layer computes the class scores for each classification category. The final label can then be determined using the maximum computed score.

One training iteration process consists of a forward pass, loss calculation, backward pass, and weight update. Random weights and biases are assigned to initialize the network. Loss is then calculated using a cost function such as cross entropy. Back propagation is performed to reduce the loss and weights and biases are updated for each layer. Through this iterative process, the final model would be determined as the weights and biases converge to some point [10]. In this method, collecting adequate training datasets is crucial for constructing a high performance model.

In this study, using the FMCW radar, baseband signals can be obtained by beating the received signal with the transmitted signal. The short time Fourier Transform (STFT) can then be applied to the demerged signal. After the STFT, two spectrograms corresponding to the up-ramp and down-ramp signals can be extracted [11]. With these signatures, it can be applied to the CNNs model as an image, and the model can classify the target. Training datasets should be provided before making the model and good datasets will give better model performance. In this study, several objects and conditions would be tested to optimize the classification model for both corner and spherical reflectors, including size, distance, and angle.

VII. CONCLUSION

In this paper, the concept for a radar system utilizing modern COTS automotive radar is presented. The radar will be capable of high-resolution sensing of targets in the competition scene due to its range resolution enabled by the wideband FMCW signal. This system will include a high-precision mechanical positioner enabling the formation of 2D and 3D images of reflectors in the scene using SAR, and the data can be input to a GMTI algorithm to allow information about moving targets to be extracted. Finally, a deep-learning model will be developed using training data of many different target types and scenes to allow the radar system to classify the detected targets.

REFERENCES