Predicting Phased Array Radar Performance through Modelling

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***Abstract*— Modelling and simulation can reduce risk associated with complex radar system development because design choices can be validated before any hardware is developed. Models can also be used to accelerate algorithm development for existing radar systems. This paper describes the modelling results for two phased array radar designs: an MTI radar and a MIMO radar. These systems were modelled and then tested with radar data generated with commercially available radar hardware. The performance results for both models and the hardware-fed processing are analyzed and compared.**

***Keywords*— Radar Modelling, Radar Simulation, MTI Radar, MIMO Radar**

I. Introduction

Radar system design projects can benefit from modelling to prove out algorithms, system design choices, and architectures before any hardware is developed. For systems that already exist, models can be used to accelerate algorithm development. To demonstrate and validate this concept, the following two radar applications were selected to model:

- Moving Target Indicator (MTI) radar
- MIMO radar

These applications were selected because they require a full cross-section of radar capabilities that can also be applied to a broader set of system designs.

Figure 1 shows a representation of the models which were used to generate and process radar data for each scenario. Once the models were completed, system level simulations were run and data was colleted.

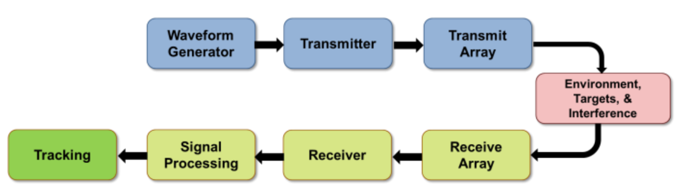

Fig. 1 – Model of Radar (targets and scenario synthesized)

For the study, a commercially available phased array radar was used to generate processed data. This data was compared to simulated data generated with the models. The selected hardware implementation also provided a source of live data for algorithm development.

The radar hardware operates at a frequency of 24 GHz and has a chirp bandwidth of up to 600 MHz. The hardware includes 2 transmit array elements and has antenna array options with either 4 or 8 receive array elements. The 4-element receive array also supports MIMO operations using the following antenna array front-end:

- 2 transmit elements with 1.5*λ spacing
- 4 receive elements with 0.5*λ spacing

The radar hardware connects to a PC via the USB interface so that waveform parameters can be programmed from MATLAB. Receive signals for each channel are first down-converted to baseband, then decimated, and transferred to MATLAB every pulse repetition interval (PRI). All processing performed after the down-conversion is done on the PC within MATLAB.

In the first part of the study, two radar models were developed using synthesized data as the test source. The next step was to verify the accuracy of the models. For this, processed results from the model were compared to the results from the live feed system as shown in Figure 2.

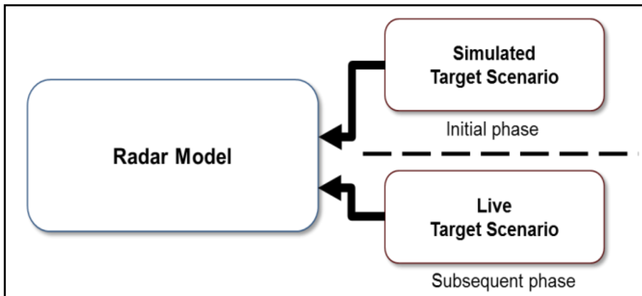

Fig. 2 – Model of Radar with synthesized or live targets

II. MTI RADAR

An MTI radar model was designed to detect a given set of low radar cross section (RCS) target profiles in the presence of ground clutter [1,2,3].

The requirements for the MTI radar were set with an eye towards future integration on a quadcopter-style platform. In the end application, the quadcopter will hover over an area and detect moving objects using the MTI radar. This scenario was used to drive the development of a synthesized data set to test the model.

The requirements for the MTI radar include:

- Target detection with RCS values of $<1m^2$ (pedestrian, drone)
- Angular resolution: < 15 degrees
- Range resolution: < 0.5m
- Maximum range in low power operations: 20m

To build a model, radar waveform parameters were computed to achieve a desired level of performance. For this project, the main waveform design parameters for an LFM chirp are the bandwidth and the pulse repetition interval (PRI). The bandwidth was selected to ensure the range resolution requirements could be achieved and the PRI was selected to ensure Doppler information could be determined for moving objects. Each of the other components shown in Figure 1 were configured to match the desired scenario.

The targets in the simulation were modelled as point targets that varied with frequency and angle to help account for the change in the targets that occur with motion and field of view angle.

The selected waveform has a 600 MHz bandwidth with a 512µsec up-chirp LFM waveform starting at 24 GHz. The waveform design is based on a desired range resolution of 0.5m (or better) to ensure multiple objects (other small drones, vehicles, or humans) could be detected from a radar mounted on a quadcopter.

To represent moving object motion dynamics in the model, parameters for range, angle, and radial motion were included to improve the fidelity of the radar simulations.

To simulate the ground clutter returns that would be seen from the quadcopter, a gamma clutter model was included in the model. To eliminate the simulated clutter (and the actual clutter returns from the ground in the measured results), a 3-pulse moving target indicator (MTI) was integrated into the model.

To ensure the paths of moving targets were captured, a multi-object tracker was integrated to track moving objects detected by the MTI radar. In the model, the synthesized moving objects were set to traverse a known pattern to help evaluate radar performance with respect to ground-truth. A radar data cube was assembled by collecting multiple sweeps of the radar waveform. The assembled data cube was then processed in range and Doppler. To improve the range-Doppler processing, beamforming was applied. CFAR detection was performed on the beamformed data. Range, radial speed, and direction of arrival measurements are estimated for the CFAR detections. These detections were then assembled and processed by the multi-object tracker.

The resulting processing from the model and simulation includes an analysis of Range-Doppler, Range-Angle, and Track History, as shown in Figure 3. The scene includes two targets located within the main beam of the radar.

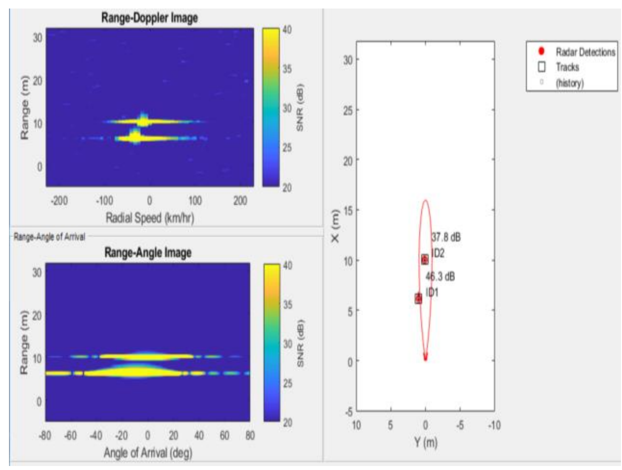

Fig. 3 – Range-Doppler, Range and Angle, and tracking with 24-GHz radar
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III. MIMO RADAR

Using the MTI model as a starting point, a model for a MIMO radar was then developed. A MIMO radar was selected as the second scenario for this paper to ensure sufficient diversity in models for the comparison with the hardware-based system [4,5]. The MIMO application that drove this use case was based on increasing the angular resolution of the system by creating a virtual array. The performance of the virtual array can be compared to the performance of the same array in non-MIMO operations.

As noted earlier, the radar hardware selected for this portion of the project has the following antenna array front-end:

- 2 transmit elements with 1.5*λ spacing
- 4 receive elements with 0.5*λ spacing

Figure 4 shows a photo of the transmit/receive array which was replicated in the array design within the model to improve fidelity. With a transmitter antenna element spacing of more than one wavelength, a MIMO transmit option can be used to form a "virtual array". The radar hardware flexibility made it possible to make multiple comparisons of model performance with both MIMO and non-MIMO operations.

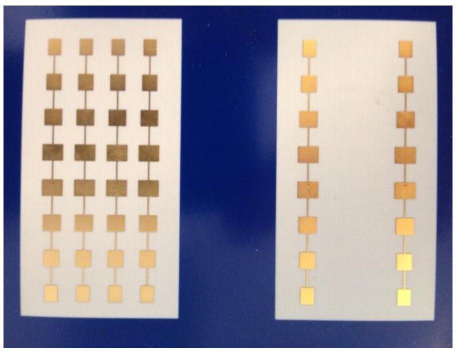

Fig. 4 – Phased array antenna – 4 Rx & 2 Tx channels

For the non-MIMO simulation and measurements, a single Tx element is used to create a broad transmit beam each PRI. With a 4-element receive array, the receive beam width is approximately 30 degrees.

MIMO operations were then implemented using alternating pulses in time (Tx pulse 1 and Tx pulse 2) from the spatially separate transmit elements. The goal was to achieve improved angular resolution (~17 degrees) over the non-MIMO operations case. The virtual array for the MIMO case was constructed by combining returns from consecutive pulses with the transmitted waveforms generated from the spatially separated transmit elements. The virtual array consists of 7 receive channels that are generated from two PRIs as follows:

Virtual Array Elements (1:3) =
Rx elements (1:3) for Tx pulse 1

Virtual Array Element (4) =
0.5*(Rx element 4 for Tx pulse 1) + Rx element 1 for Tx pulse 2)

Virtual Array Elements (5:7) =
Rx elements (2:4) for Tx pulse 2

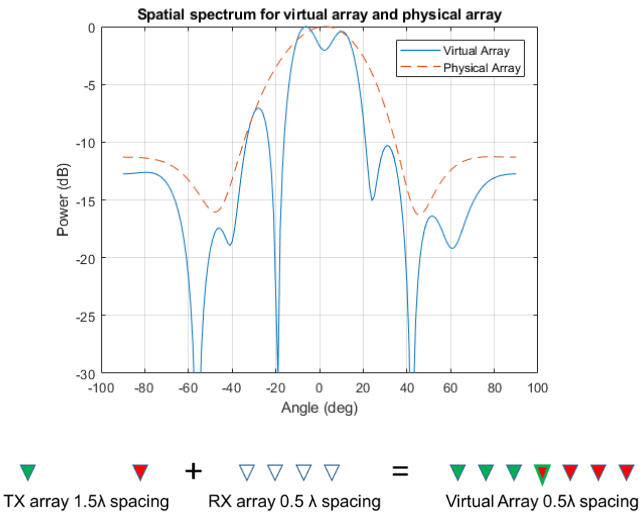

Fig. 5 – Virtual Array vs. Physical Array Spatial Spectrum

Figure 5 shows how the spatial spectrum which was generated from the model to test our algorithm in simulation before testing with live data.

IV. Processing Live Radar Data

Once the system modelling was complete, the radar hardware was used to feed the same signal processing algorithms used in each of the models.

As noted earlier, one of the goals of our project was to make the model match as closely as possible to the end system. This drove various techniques to help improve the fidelity.

The radar model was used to determine and set the proper threshold levels for both the noise figure and the detection levels. A test harness was implemented to locate stationary targets using the hardware to illuminate a specific field of view. In addition, test targets were set up to move through the field of view across a range of azimuth and range values. This ensured that the detections for the simulation matched the "ground truth" values which were synthesized independently.

Data recording was implemented to help capture difficult scenarios and aid with system debug, algorithm refinement and playback.

For the measurements, the model was used to create a positional map to place targets at specific locations to measure angular resolution.

Several experiments were performed using higher and lower pulse repetition frequencies to improve Doppler processing.

Figure 6 shows data collected from the MTI radar hardware, which matched the simulation results described earlier.

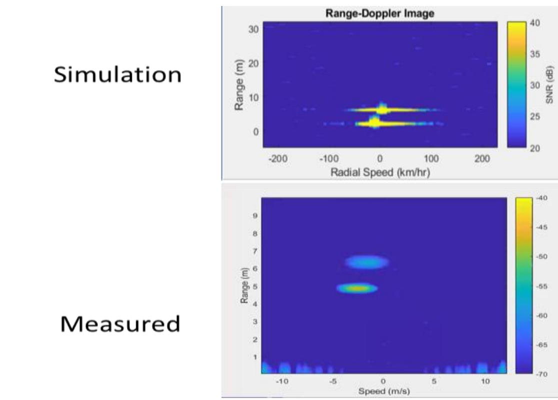

Fig. 6 – Range-Doppler for two targets *

This model was then run with streaming radar data using a quadcopter moving through the field of view. Figure 7 shows the scene with the detection in the range-angle plot and the track shown in the bird's-eye plot.

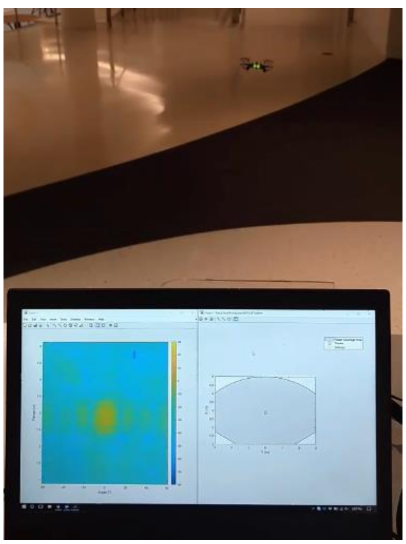

Fig. 7 Quadcopter detection and track with live radar

Figure 8 shows four plots with range vs. angle for both MIMO and non-MIMO operations. The simulation and measured preliminary results are compared for the same scenarios.

The results confirm that the simulation and measured agree. The objects in the scene are separated by 25 degrees and are located at the same range. In the MIMO case (measured and simulated), two targets are resolved. In the non-MIMO case, the two targets appear as a single target.

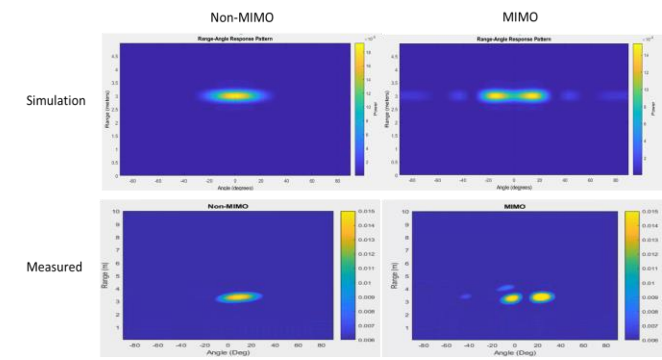

Fig. 8 – Range-Angle plots – for MIMO and non-MIMO (simulated vs. measured)*

V. Conclusion

Modelling and simulation can be used to design and implement complex radar systems. For this paper, we implemented models for an MTI radar and a MIMO radar. The modeling and simulation results were validated with both synthesized data and live data taken from a radar.

In the case of the MTI radar, all requirements were achieved with the corresponding radar model. The performance of the design was subsequently replicated using the radar hardware. The 8-channel receive array provided sufficient resolution in azimuth and the 600 MHz LFM waveform ensured the range resolution requirement was met. Other algorithms including CFAR, beamforming, and tracking could be validated using the model prior to hardware integration.

In the MIMO design, we created a virtual array to increase angular resolution. Simulation and live system data processing yielded the same ability to resolve two targets where the non-MIMO operations resulted in a single target for the same scenario.

In future work, we will apply this system to quadcopter detection and identification. The system models provide a way to improve efficiencies with future live data collection efforts.

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* Generated with Phased Array System Toolbox™