

Radar Tracking of Small Moving Targets from an Hybrid Detection Algorithm using MUSIC and FFT

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Abstract—In this paper, we propose to combine the two-dimensional MUSIC (Multiple Signal Classification) algorithm with Fast Fourier Transform (FFT) to detect small moving targets from raw data collected by millimeter-wave beamscanners. It is shown that this hybrid detection method makes it possible to reduce by factor 3 the computation time required by MUSIC algorithm, at the expense of the reduction by 55% of the detection rate. Measurement results and analyses are given in the case of the tracking of a small mobile cylinder in a cluttered indoor environment from three millimeter-wave beamscanning radars.

I. INTRODUCTION

Nowadays, high-resolution millimeter-wave (mm-wave) Modulated Continuous-Wave (FM-CW) systems are widely used in many military and industrial applications, as they offer large bandwidth (high-resolution) and good robustness to environmental conditions. Moreover, techniques based on Fast Fourier Transform (FFT) have been advantageously used to mitigate radar interference [1], while MUSIC (Multiple Signal Classification) algorithms have been widely developed in many radar applications to estimate the Direction of Arrival of electromagnetic waves (see, e.g., [2]). Recently, the authors of the present study have reported a clutter mitigation technique based on MUSIC processing of mm-wave radar images [3] and they applied this technique to the detection of small targets in a cluttered environment. In this paper, we propose a novel hybrid detection algorithm for the tracking of small moving targets that consists of applying MUSIC and FFT algorithms to the raw data collected by millimeter-wave beamscanners.

II. MILLIMETER-WAVE RADAR IMAGING SYSTEM

To generate mm-wave radar images, we use here the *RBK2* FM-CW MIMO radar working at 77GHz and commercialized by *INRAS GmbH*. This sensor steers the radar beam electronically in azimuth by using $N_C = 16$ channels. In front of the sensor's antennas, we add a rotating reflector (see Figure 1) that mechanically steers the beam in elevation with the rate of 16.7 scans per second. The theoretical range resolution is of 5cm. In our previous work [3], we applied a 2D-MUSIC algorithm to estimate the range-azimuth pseudo-spectrum defined in [2] in each elevation plane from the raw radar images collected by the mm-wave radar imaging system. However, this estimation requires high computation time and large memory resources. To significantly reduce the time required to compute range-azimuth pseudo-spectra, we propose in section III to use 2D-MUSIC only in certain regions of the

detection volume, while the rest of the volume is processed by applying a 2D-FFT algorithm.

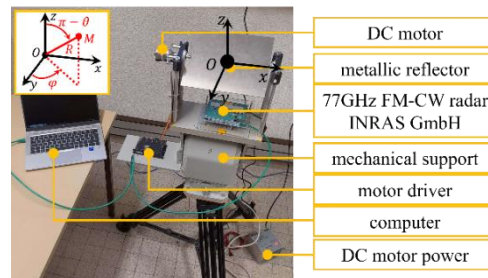


Figure 1. Annotated photo of mm-wave FM-CW radar setup used to track small moving targets in 3D space. The Cartesian (x , y and z) and spherical coordinate systems (R , θ and φ) are shown respectively in black and red. The origin of axes is at the center of the rotation axis of the metallic reflector.

III. TARGET DETECTION FROM 2D-MUSIC AND 2D-FFT

From the measurement results reported in Table I, it can be observed that the detection volume in which a small target is accurately located is significantly larger when mm-wave radar images are processed by using 2D-MUSIC algorithm rather than a 2D-FFT algorithm. However, this benefit is obtained at the cost of prohibitive time to compute the range-azimuth pseudo-spectrum needed to detect the target of interest in the volume scanned by the radar beam. To reduce the computation time without impacting the size of the detection volume, we propose here to segment the scanned region R_{tot} into 5 disjoint regions $R_{M,1}$, $R_{M,2}$, $R_{M,3}$, $R_{M,4}$ and $R_{M,5}$ in which the pseudo-spectrum is estimated from a 2D-MUSIC algorithm, and one region R_C in which the pseudo-spectrum is determined from 2D-FFT (see Table II and Figure 2 for the definition of the regions). The following steps are followed to estimate the spatial coordinates of moving targets in each region from the raw data collected by the mm-wave radar imaging system: (i) the range-azimuth image is determined from applying a 2D-FFT on the raw data; (ii) the resulting image is cropped from using the prescribed boundaries of each region (in our example, the boundaries are defined in Table I); (iii) the inverse 2D-FFT is applied on this new range-azimuth image to obtain the so-called *resampled raw data*; (iv) a pseudo-spectrum is then estimated from the resampled raw data by using either 2D-MUSIC or 2D-FFT (in our example, Table II associates each region to an algorithm); (v) Zero-padding is applied to the estimated pseudo-spectrum; and finally, (vi) spatial coordinates of the target are estimated from the method reported in [3].

TABLE I. DETECTION VOLUME OF THE MM-WAVE RADAR IMAGING SYSTEM BY USING ONLY 2D-MUSIC OR 2D-FFT.

| Algorithm | Definition of the detection volume* | | | Detection volume |
|-----------|-------------------------------------|----------------------------------|--------------------------------|------------------|
| | $[R_{min}, R_{max}]$ | $[\varphi_{min}, \varphi_{max}]$ | $[\theta_{min}, \theta_{max}]$ | |
| 2D-MUSIC | $[0.0, 2.7m]$ | $[-45^\circ, 45^\circ]$ | $[60^\circ, 120^\circ]$ | $10.25 m^3$ |
| 2D-FFT | $[0.7m, 2.1m]$ | $[-15^\circ, -25^\circ]$ | $[85^\circ, 105^\circ]$ | $0.72 m^3$ |

* see Figure 1 for the definition of the spherical coordinates

TABLE II. DEFINITION OF THE SIX REGIONS USED TO SEGMENT THE DETECTION VOLUME AND THE CORRESPONDING ALGORITHMS.

| | Spherical coordinates of the six regions | | | Detection volume | Algorithm |
|-----------|--|----------------------------------|--------------------------------|------------------|-----------|
| | $[R_{min}, R_{max}]$ | $[\varphi_{min}, \varphi_{max}]$ | $[\theta_{min}, \theta_{max}]$ | | |
| $R_{M,1}$ | $[0.0m, 0.7m]$ | $[-45^\circ, 45^\circ]$ | $[60^\circ, 120^\circ]$ | $0.18 m^3$ | 2D-MUSIC |
| $R_{M,2}$ | $[0.7m, 2.0m]$ | $[-45^\circ, -15^\circ]$ | $[60^\circ, 120^\circ]$ | $1.37 m^3$ | 2D-MUSIC |
| $R_{M,3}$ | $[0.7m, 2.0m]$ | $[25^\circ, 45^\circ]$ | $[60^\circ, 120^\circ]$ | $0.90 m^3$ | 2D-MUSIC |
| $R_{M,4}$ | $[0.7m, 2.0m]$ | $[-15^\circ, 25^\circ]$ | $[60^\circ, 85^\circ]$ | $0.73 m^3$ | 2D-MUSIC |
| $R_{M,5}$ | $[0.7m, 2.0m]$ | $[-15^\circ, 25^\circ]$ | $[105^\circ, 120^\circ]$ | $0.43 m^3$ | 2D-MUSIC |
| R_C | $[0.7m, 2.0m]$ | $[-15^\circ, 25^\circ]$ | $[85^\circ, 105^\circ]$ | $0.61 m^3$ | 2D-FFT |

* see Figure 1 for the definition of the spherical coordinates

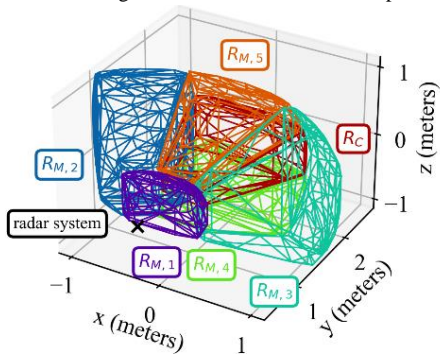


Figure 2. 3D representation of the six regions $R_{M,1}$, $R_{M,2}$, $R_{M,3}$, $R_{M,4}$, $R_{M,5}$ and R_C used to segment the detection volume.

To experimentally validate the expected reduction of computation time when using 2D-MUSIC in the regions $R_{M,1}$, $R_{M,2}$, $R_{M,3}$, $R_{M,4}$ and $R_{M,5}$ and 2D-FFT in the region R_C , a small metallic cylinder (2cm long and 3mm wide) was moved during 60 seconds back-and-forth along the x -axis in front of three identical mm-wave radar imaging systems (see radars #1, #2 and #3 in Figure 3). The cumulative detection volume is of $4.23m^3$. The cartesian coordinates of the target detections resulting from the application of the proposed technique on raw data collected by the three radars are displayed in Figure 4. The estimation of pseudo-spectrum was performed by using a HPC cluster of 16 CPUs (Intel E5-2695 v4 2.1G) mounted in parallel with a total RAM of 240GB. Total computation time required to estimate the pseudo-spectrum is of 1,225 seconds from the raw data of radar #1 and of 3,175 seconds when using 2D-MUSIC in the entire detection volume (see Table III). However, the detection rate (that is, the ratio between the number of target detections and the total possible detections) is of 51% (510/1000) when using the proposed hybrid method combining 2D-MUSIC with 2D-FFT, while it is of 79% (789/1000) when using only 2D-MUSIC. Therefore, 2D-MUSIC algorithm achieves higher detection rate (+55%) than the proposed method, but at the expense of significantly larger (+160%) computation time.

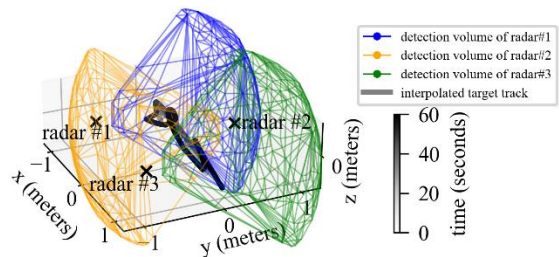


Figure 3. Spatial areas illuminated by three mm-wave beamscanning radars. The obtained 3D tracking of the target is displayed in gray scale.

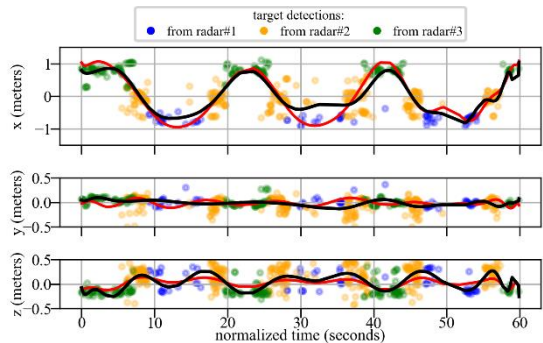


Figure 4. Target trajectories (in black) estimated from the proposed MUSIC/FFT hybrid method and from the MUSIC only (in red).

TABLE III. DETECTION VOLUME AND COMPUTATION TIME FOR THE SIX REGIONS DEFINED IN TABLE II AND FOR RADAR #1.

| | Algorithm | Detection volume (m^3) | computation time (s) |
|-----------|-----------|----------------------------|----------------------|
| $R_{M,1}$ | 2D-MUSIC | 0.18 | 415 |
| $R_{M,2}$ | 2D-MUSIC | 1.37 | 329 |
| $R_{M,3}$ | 2D-MUSIC | 0.90 | 226 |
| $R_{M,4}$ | 2D-MUSIC | 0.73 | 158 |
| $R_{M,5}$ | 2D-MUSIC | 0.43 | 84 |
| R_C | 2D-FFT | 0.61 | 13 |

IV. CONCLUSION

We have reported the 3D tracking of a small metallic target by a mm-wave beamscanner from a hybrid MUSIC/FFT detection technique. This technique allows reducing significantly the computation time required by MUSIC algorithm, at the expense of a lower detection rate.

V. ACKNOWLEDGMENT

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REFERENCES

- [1] J. Bechter, K. Eid, F. Roos, and C. Waldschmidt, 'Digital beamforming to mitigate automotive radar interference', in *2016 IEEE MTT-S ICMIM*, San Diego, CA, USA: IEEE, May 2016.
- [2] B. A. Karim and H. K. Ali, 'Computationally efficient MUSIC based DOA estimation algorithm for FMCW radar', *J. Electron. Sci. Technol.*, vol. 21, no. 1, p. 100192, Mar. 2023.
- [3] E. Dedic, A. Hadj-Djilani, D. Henry, M. Lihoreau, H. Aubert, '3D Tracking of Small Moving Targets in Cluttered Environment from the Isolines Processing of Millimeter-wave Radar Images', in *2023 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, Portland, OR, USA: IEEE, 2023.