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3D Tracking of Small Moving Targets in Cluttered Environment from the Isolines Processing of Millimeter-wave Radar Images

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Abstract— In this paper, we report a three-dimensional tracking technique of small moving metallic targets in a cluttered environment using millimeter-wave Frequency-Modulated Continuous-Wave radars. Trajectories are determined from the estimation of the Direction of Arrival of signal backscattered from targets illuminated by the steerable radar beam. The electromagnetic clutter is mitigated thanks to an original image processing technique based on isolines, that is, lines in the radar images along which the echo level is the same. Our targeted application is the indoor detection at short range (up to 1.5 meters for a single radar) of tagged flying insects for behavioral studies.

I. INTRODUCTION

How flying insects move in space is a central question in behavioral and ecological sciences. Over recent years, radar technologies have been used to track the 2D flights of various insects [1]. The two main radar techniques used for this purpose are harmonic radar [2] and radio telemetry [3]. These approaches allow detecting insects for large distances (several hundred meters) at the cost of poor spatial and temporal resolutions. Although this is an important first step, tracking the 3D trajectories of these animals is essential to understanding their navigation behavior, even if this is achieved at short ranges.

Recently, the authors of the present study have demonstrated that a radar system can be used in ethology to track multiple untagged flying insects in 3D space [4]. This technique uses a Frequency-Modulated Continuous-Wave (FM-CW) millimeter-wave radar that scans the scene from a digital beam-scanning in azimuth and a mechanical beam-scanning in elevation. Flying insects have been successfully detected by applying this approach in environments with low electromagnetic clutter. However, from an ethological point-of-view, it would be more interesting to study the behavior of flying insects in highly cluttered and natural environments.

In this paper, we propose a new technique for the 3D tracking of small moving metallic tags in cluttered and/or natural environments. It consists of computing isolines, that is, lines in millimeter-wave radar images along which the echo level is the same. Our targeted application is the detection at short range (i.e., a few meters away) of tagged flying insects for behavioral studies.

II. MECHANICAL SCANNING OF RADAR BEAM

To detect in cluttered environments small metallic tags with size of a few centimeters, we use here a FM-CW Multiple-Input Multiple-Output (MIMO) low-cost radar operating in the millimeter-wave frequency range. This radar is the RadarBook2 (RBK2) radar from *INRAS GmbH* operating at 77.5GHz. This radar performs the digital beamforming in azimuth plane from one transmitting (Tx) linearly-polarized antenna array of 2-by-6 metallic patches and 16 receiving (Rx) linearly-polarized antenna arrays of 1-by-6 metallic patches. We place at 15cm in front of the radar front-end a large rotating reflector (rectangular metallic plate of dimensions 20cm x 25cm) to steer the radar beam in elevation plane (see Fig. 1). The frame rate resulting from the rotation of the reflector is of 16 frames per second. The transmitted electromagnetic power is of 10mW. As the radar frequency bandwidth is of 3GHz, the theoretical range resolution is of 5cm.

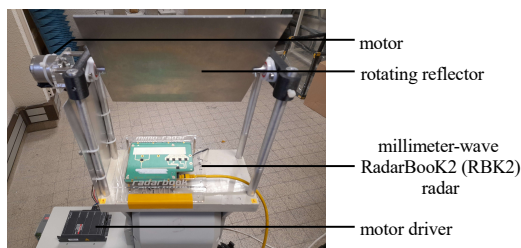


Fig. 1. The FM-CW MIMO radar setup at 77.5GHz used to track small moving metallic tags in 3D space. The scanning of the radar beam is performed mechanically in elevation plane from the rotation at 500rpm of the reflector.

Raw data received by the 16 Rx channels are collected with a measurement repetition time of 1ms, while the reflector is rotating at around 500rpm. As reported in [4], the inevitable fluctuation of the rotation speed is here estimated from the temporal distribution in the beat frequency spectrum of large peaks generated by the electromagnetic backscattering of the reflector. The MUSIC (MUltiple Signal Classification) algorithm [5] is applied for each estimated elevation angle to derive from raw data the range and azimuth angle of detection points. In addition, the 3D location of these points is extracted from the processing of 3D radar images by computing isolines, (see [6] for details on isoline processing of radar images). The proposed beam-steering radar system allows estimating the location of metallic cylinders with height of few centimeters at a distance up to 1.5 meters with a measurement uncertainty of $\pm 2.5\text{cm}$. The direction of the target is estimated with uncertainties of $\pm 0.5^\circ$ in the azimuth plane and of $\pm 2^\circ$ in the elevation plane. For such small targets, the detection volume for a single radar is found to be of about 2.2m^3 . To enlarge the detection volume, several low-cost radar systems can be deployed. The calibration of the resulting radar set up is performed from illuminating the scene in presence of motionless tags. This step allows to determine the coordinates transformation needed to enable the merging of images obtained from multiple radars. As an example, two radars of Fig. 1 were placed in front of each other at a distance of 4m and a tag (that is, a metallic cylinder of 2cm long) has been moved from one radar to the other during 30 seconds. The cartesian coordinates of detection points as a function of time derived from both radars are displayed in Fig. 2, where the y-coordinate is taken along the axis joining the two radars. We observe that the variation of this coordinate accurately reflects the actual round-trip movement of the tag up to 3 m.

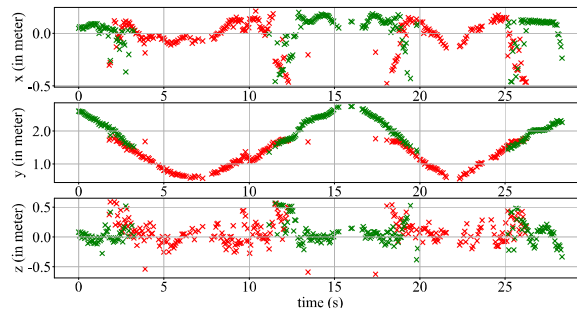


Fig. 2. Cartesian coordinates of detection points versus time. Points detected by radar #1 are indicated in red, and those detected by radar #2 are in green.

III. MITIGATION OF THE ELECTROMAGNETIC CLUTTER

The detection of small moving targets, such as tagged flying insects [3], by using a radar system requires in practice the mitigation of the electromagnetic clutter, that is, the reduction of the electromagnetic backscattering from the environment. For this purpose, we propose here to process radar images by using isolines. The image processing consists of the following steps: (i) Scanning the scene with the radar beam in absence of the targets of interest. The set of 3D radar images are then recorded and ordered by increasing time; (ii) Computation of isolines in radar images along which the echo level is the same. These lines form contours named *isolines* within which the location of the highest amplitude of the radar echo is determined. Inside a contour, if this amplitude is larger than a predefined threshold (8dB here), we consider that the contour has localized a contributor to the electromagnetic clutter. This contour is then called a *clutter contour*; (iii) Development of steps (i) and (ii) in presence of targets. The spatial coordinates of detection points are then given by the location of the highest amplitude of the radar echo inside each computed isolines. If it is found inside one of the clutter contours determined at step (ii), the detection point is considered as a contributor to the electromagnetic clutter and is then discarded. Otherwise, it is considered to be the target of interest; and finally, (iv) Derivation of the trajectory of targets from the barycentre of all sets of points detected at each frame. To illustrate these steps to mitigate the electromagnetic clutter, a metallic cylinder of 2cm long has been moved in front of a single radar. Moreover, in order to increase the clutter, we have placed a fixed metallic ball with diameter of 5 cm at the centre of the scene. The tag is far enough from the metallic ball (i.e., at least 17 cm) to detect without ambiguity its 3D location at each frame. The detection points obtained from the isoline-based image processing are displayed in Fig. 3(a). We have observed that 1219 detection points over 1349 points (90.4%) that are collected at step (iii) were discriminated as a contribution to the electromagnetic clutter. Therefore, only 130 detection points over 1349 points (9.6%) are associated to target detections. At step (iv) 112 detection points have finally been selected to draw the trajectory displayed in Fig. 3(b).

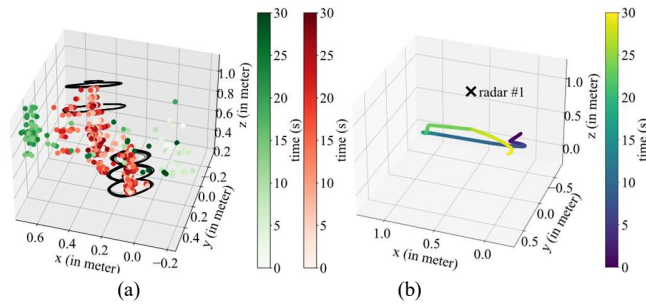


Fig. 3. Illustration of the isoline-based image processing of radar images to mitigate the electromagnetic clutter: (a) Clutter contours are shown in solid black lines, clutter detection points are indicated in red while those that originate from the tag are in green; (b) Estimated trajectory of the tag after the clutter mitigation for a duration of 30s.

IV. CONCLUSION

We have reported the 3D tracking of a small metallic tags in a cluttered environment using a FM-CW MIMO radar system. We have illustrated a new technique based on isolines to mitigate the electromagnetic clutter. In future work we will apply the proposed technique to track tagged flying insects.

V. ACKNOWLEDGMENT

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