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Multistatic Radar Imaging for Traffic Monitoring

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***Abstract*—This work presents a novel radar system for vehicle imaging. The proposed system is based on estimation of target parameters like range and velocity and generation of the final radar image. For this purpose, a multistatic Frequency Modulated Continuous Wave (FMCW) Synthetic Aperture Radar (SAR) system is implemented. Both the simulation and on site measurements show that such a radar system has the potential to replace the current very expensive sensors.**

I. Introduction

A considerable number of technologies are currently available for traffic flow monitoring in the literature [1]. These sensors are installed to gather information about the flow of the traffic within a cross section of the road. The major aim is to estimate the parameters like the lane occupancy, number of vehicles per lane, velocity per vehicle, average velocity per lane and the classification of the vehicles by their lengths.

Three sensors are frontiers for extracting these information: The video cameras [2], the inductive loop sensors and LIDARs. The cameras are very effective for imaging the targets however they are light sensitive and demands extensive maintenance due to the dirtiness that makes the cameras blind in compelling weather conditions. Unlike cameras, LIDARs are active devices that are not sensitive to the change of light but still requires maintenance; like the lenses must be frequently cleaned. One of the most efficient and highly accurate sensor is the inductive loop. Nevertheless, just like video cameras and LIDARs, inductive loops require intrusion to the road. The inductive loops shall be installed to the ground and if a failure occurs, the asphalt on the road shall be reconstituted. The camera and the LIDAR shall be installed to the tags that are constructed on the road. If maintenance of the sensor is required, part of the road shall be temporarily closed. In addition, these sensors shall be installed for each lane; results in a very cost inefficient solution.

The Linear Frequency Modulated Continuous Wave (LFMCW) radar is commonly used in many applications including automotive driver-assistance, room-occupancy sensing and industrial automation [3]. There are some efforts for using the radars in traffic monitoring applications and vehicle classification. In [4], micro-Doppler signatures are used for the classification in the traffic intersections. The input of the classifier is only the range of the target. In [5], estimation of range, velocity and acceleration is achieved to extract the range-Doppler image of the scene by installing a front fire radar. However, the spatial (range-azimuth) image of a target is totally different from the range-Doppler image that is obtained in these methods. In order to extract the two dimensional image of the target, the radar may be installed such that the direction of the radar is perpendicular to the direction of the traffic flow; this geometry is termed as side fire. A major advantage of this geometry is that the azimuth profile is not dependent to angular accuracy of the sensor as is the case for the front fire geometry.

In the side fire geometry, the azimuth profile is a function of range and velocity of the target and the antenna pattern of the radar. A reliable length estimation is achievable only in the case that both of these parameters are known. The range estimation is straightforward with the current LFMCW waveforms. However the velocity estimation with the traditional range Doppler method is no longer valid as the relative velocity is quite different from the actual one in the side fire geometry. For this purpose, one way is to apply an Inverse Synthetic Aperture Radar (ISAR) signal processing algorithm for estimating the velocity. The traffic monitoring applications like red light or speed enforcement require a highly accurate and reliable speed measurement that cannot be achieved with the current ISAR techniques. Another method is to increase the number of sensors along the road [6] so the transition duration of the vehicle from one radar to the other can be estimated. By this way, a dual radar can be used for estimating the velocity of the vehicles by using the Displaced Phase Center Antenna (DPCA) techniques.

The SAR principle is a quite mature technique that can be used for imaging vehicles for the traffic monitoring purpose. There is even an effort for satellite SAR imaging of the fixed automotive vehicles [7]. However the moving target imaging is much more complicated.

In this work, a multistatic LFMCW radar system to obtain the ISAR image of vehicles is proposed. By using this system, it is shown that both the range, velocity and range-azimuth image of the target can be extracted in the side fire geometry. In the next section, the problem definition and the imaging algorithm will be explained. Then the parameter estimation will be described. In the fourth section, the algorithm flow will be explained. The fifth section is dedicated to the simulation and on site tests. Last section is the conclusion.

II. Problem Definition

The proposed side fire geometry is shown in Figure 1. The radar line of sight is perpendicular to the direction of the

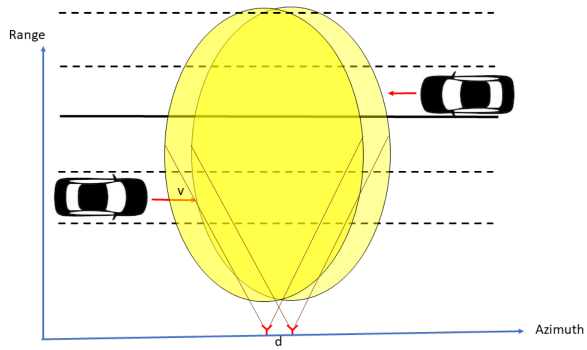

Fig. 1. The traffic monitoring system

traffic flow. There are two radars that have overlapping antenna footprints. The radars are located along the road traffic flow direction with a distance d apart from each other.

The transmitted signal is an LFMCW that can be expressed as follows:

$$s_t(t) = exp(j2\pi(f_c t + \frac{\alpha}{2}t^2) \tag{1}$$

The received signal from a point target at an initial range and azimuth position (r_0, x_0) and an azimuth velocity of v is

$$s_r(t) = a_t(r_0, \eta_0)exp(j2\pi(f_c(t - \frac{2R}{c}) + \frac{\alpha}{2}(t - \frac{2R}{c})^2) \quad W_a(\eta, \eta_0, \eta_{dc}) \tag{2}$$

where a_t is the amplitude of the received signal, R is the range that can be expressed as:

$$R = \sqrt{r_0^2 + (vt + v\eta - x_0)^2} \tag{3}$$

where η is the slow time and W_a is the antenna pattern, $\eta_0 = x_0/v$ is the initial time of the target, η_{dc} is the azimuth time of the Doppler centroid. The FMCW radars are mostly homodyne receivers that mixes the transmitted signal and the received one directly in order to decrease the bandwidth of the signal. After mixer and low pass filtering, the IF signal can be written as follows:

$$s_{IF}(t, \eta) = \gamma(r_0, \eta_0)exp(-j2\pi(f_c + \alpha t)\frac{2R}{c})W_a(\eta, \eta_0, \eta_{dc}) \tag{4}$$

where γ represents the amplitude of the received signal after the receiver antenna and all the succeeding amplifiers, attenuators and filters that are assumed to be phase preserving.

In the pulsed SAR systems, the duration of the pulses are mostly very short. So the target movement within the pulse is almost always neglected. This is known as the stop and go approximation that the movement of the target between the receive and transmit is neglected. However, in the FMCW case, this assumption is no more valid [8].

In order to express the impact of the target movement within the chirp, the Fourier transform in the azimuth domain is derived analytically. Let us denote $K_r = \frac{2(f_c+\alpha t)}{c}$ as this term includes solely the fast time. The Fourier transform according to the azimuth time of the signal can be written as follows:

$$S_{IF}(t, f_\eta) = \int s_{IF}(t, \eta)exp(-j2\pi f_\eta \eta)d\eta \tag{5}$$

The principle of stationary phase [9] can be applied in order to derive the Fourier transform of the received signal:

$$s_{IF}(t, f_\eta) = \gamma(r_0, \eta_0)exp(-j2\pi r_0\sqrt{K_r^2 - \frac{f_\eta^2}{v^2}}) \quad exp(-j2\pi(-f_\eta t + f_\eta x_0/v)) \quad W_a(f_\eta, \eta_0, f_{dc}) \tag{6}$$

The first exponential is known to be the Fourier transform of the traditional stop-and-go approach SAR signal, while the second exponential include the movement of the target within the chirp and the initial timing of the target. To develop a SAR imaging scheme, as it is presented in the equation, range and velocity to the target, Doppler centroid frequency and the initial time of the target shall be estimated. The ISAR imaging can be achieved after compensation of the second exponential and Doppler centroid. The remaining term is belonging to the classical ISAR signal and there are many methods for image formation. In this work, a 2D matched filtering is used to reveal the potential of the proposed system.

III. Parameter Estimation

Traditional ISAR imaging algorithms assume a single target within the area of interest. However this is not the case for the traffic monitoring scenario as it is shown in Figure 1. In this case, there may be multiple targets in different ranges with quite different velocities. Hence, an isolation of the signal corresponding to the target is required. Targets have at least three distinctive properties that can be estimated by the radar: Range, velocity and the length. Here, the targets are discriminated in range due to its easiness.

A. Range Estimation

To apply the 2D matched filtering, the estimation of the range is not required. The reference filter can be generated to cover all the possible instrumented ranges. However, this method is very computationally complex. In addition, to estimate the velocity of the target, the range profiles will be already extracted. So a detection algorithm can be used to isolate the targets and dramatically decrease the number of ranges of interest. This is also not only an improvement but also a prerequisite for the traffic monitoring radars that mostly includes very limited signal processing hardware.

After taking the FFT of the signal and the thresholding, the range to the target can be estimated via:

$$f_b = \alpha\frac{2R}{c} \tag{7}$$

where f_b is the beat frequency.

B. Velocity Estimation

The velocity of the target is estimated by the DPCA method with the dual radar system that is presented in Figure 1. In this case, the two azimuth profiles is a shifted version of each other as far as identical radars are assumed. The time difference of the azimuth signal between channels can be expressed as:

$$\Delta t = \frac{d}{v} \tag{8}$$

The velocity is estimated by cross correlating the two channels and computing the shift of the peak. In order to increase the accuracy of the estimation, the distance between the radars must be longer. The upper limit is that the scattering from different azimuth angle must still satisfy a sufficiently high cross correlation. The relation between the accuracy percentage and the distance between the radar, d, can be written as follows:

$$Accuracy(\%) = 100\frac{v_{max}\tau}{d} \tag{9}$$

where v_{max} is the maximum velocity of the vehicle and τ is the duration of the chirp. The accuracy of the estimation can be improved by interpolation [10] or super resolution methods [11].

C. Doppler Centroid Frequency (DCF) Estimation

In the side fire geometry, the radar boresight is aimed to be perpendicular to the road traffic flow direction. Otherwise a shift in Doppler bandwidth occurs and the SAR imaging window moves out of the boresight of the antenna. This may result in poor radiometric resolution for the final SAR image. The radar can be fine tuned so as to satisfy zero DCF. However, the radars may be intentionally installed to some locations like a turnout that the multiple lanes are not satisfying this condition. In order to insert more flexibility to the both installation procedure and location of the radar, a squinted geometry is not only demanded but also unavoidable. The DCF and its relation with the azimuth time, η_{DC} that is mentioned in Equation 4 can be expressed mathematically as:

$$f_{dc} = \frac{2v^2}{\lambda R}\eta_{dc} \tag{10}$$

In the proposed system, the DCF is variant for each target as the velocity of each target is different; something specific to ISAR and not SAR that the DCF can be estimated by using the whole data. For the proposed system, the range profiles are extracted and given as input to the DCF estimation step. There are various methods for estimation of the DCF. In this work, the DCF is estimated by splitting the power spectrum into two and finding the frequency where the energy is as close as possible in both sides as it is described in [12].

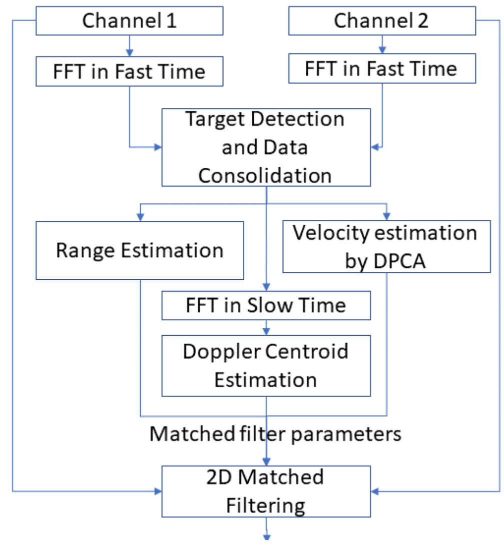

Fig. 2. Algorithm flow of the proposed method

TABLE I
MAIN PARAMETERS OF THE FMCW RADAR.

Parameter	Value	Unit
Center Frequency	24.125	GHz
Bandwidth	250	MHz
Sampling Frequency	125	kHz
Chirp Duration	1	msn
Unambiguous Range	38.4	m
Distance between antenna	50	cm
Azimuth beamwidth of the antenna	6	degree

IV. METHOD

To clarify the proposed method, the algorithm flow is presented in Figure 2. The output of each radar channel are the digitized IF signal. The first step is the FFT in fast time. The amplitude of the signal is given as input to the target detection algorithm. The detected bins are consolidated and a slow time profile of the target is extracted. The range estimation is achieved as in Equation 7. Then the DPCA algorithm for two channels is applied for time difference and as a result velocity estimation as in Equation 8. The frequency spectrum of the signal is obtained by the FFT in slow time. The Doppler centroid frequency is estimated as it is described in [12]. The estimated range, velocity and Doppler centroid frequency is used to obtain the 2D matched filter and convoluted with the channel output to extract the final ISAR image.

V. RADAR SYSTEM DESIGN

The radar system parameters are shown in Table I. The K band and 250MHz bandwidth is chosen as this is the allowed ISM band for the traffic monitoring radars.

The range resolution is 0.6m and each chirp is digitized up to 128 real samples to fulfill two specifications of the system: The first is the maximum range to be 38.4m. Second is that the vehicles is associated with the lanes accurately. Typically, the width of the lanes is approximately 3.5m.

The chirp duration shall be chosen so as to avoid aliasing in the Doppler bandwidth. The maximum target velocity is assumed to be 50m/sn that corresponds to 977Hz in K band. So the sampling frequency is selected so as to achieve a chirp duration of 1msn which yields a 1kHz bandwidth.

The isolation of the target is important for parameter estimation and is achieved if there is a range difference between the targets. So the number of targets in the same range must not be more than one. That is why, a narrow beam antenna in the azimuth direction shall be chosen for the proposed system. The maximum value of the illuminated azimuth footprint with the parameters in Table I is approximately 4m that is comparable with the length of a single car and is a distance that is less likely long enough to include multiple vehicles.

Another system parameter is the distance between the radar antenna phase centers. For a maximum velocity of 50m/sn, and velocity accuracy of 10% and 1msn chirp duration the minimum distance between the radars shall be at least 50cm. We emphasize that this can be improved by fine estimation of the frequency.

The multiplexing of two LFM's can be achieved in a time division or a frequency division manner. A frequency division without interference is achievable as the bandwidth of the received signal is quite narrow comparing with the sweep frequency. In this case, the frequency stability of the sensors shall be guaranteed not to interfere to each other. In the time division case, the multiplexing can be done between the chirps and within the chirps. The previous one may result in poor cross correlation of the received signal while the second one requires a highly accurate synchronization. For this purpose frequency division multiplexing with synchronizing the initial timings of the chirps is followed.

VI. RESULTS

In this section, the results of the simulation and on site experiments will be discussed. The parameters of both is given in Table I.

To show the performance of the method, 6 point targets are located to simulate a vehicle of size 3m by 3m. The steps of the simulation is as follows: Raw data simulation, FFT in fast time, velocity estimation, FFT in azimuth, DCF estimation, reference function construction and multiplication with the raw data. The output of the FFT and the final ISAR image are presented in Figure 3. In the upper part of the figure, it is seen that the target is smeared in azimuth as this is an unfocused radar image. However in the below image, the point targets are focused that results in accurately estimating the length of the target.

In the next step, the performance of the proposed algorithm for the real traffic case is assessed by using two commercially available FMCW radars that are located along the road direction. Both of the radars transmit the LFMCW signal with the parameters that are given in Table I. The radars are synchronized to each other by using the same clocks to

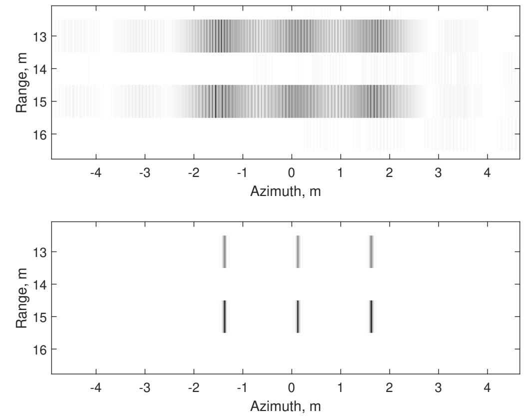

Fig. 3. Simulation results for the 6 point targets case. Up: The fast time FFT of the received signal. Down: After the proposed method is applied

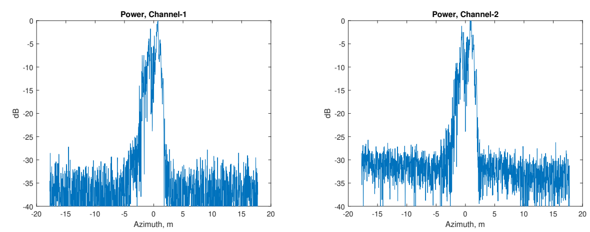

Fig. 4. Azimuth profile of the vehicle for two channels

initialize the waveform. The received data is digitized after low pass filtering.

In Figure 4, the power distribution of a vehicle versus the azimuth is shown for two channels. The estimated velocity for this target is 22.9m/sn. The azimuth time of the target is multiplied by the estimated velocity to extract the azimuth axis in meter. As it is shown, it is not easy to estimate the length of the target due to the range and antenna pattern dependency of the azimuth profile. A target at a different range will have a different radar azimuth image that results in poor classification accuracy. The same is the case for different antenna patterns and squint angles.

In the next step, the DCF is estimated and the phase compensation is done. In Figure 5, the power spectrum versus Doppler frequency of the target is shown. The squint angle is estimated to be 2.85 degree and the DCF is 179.1Hz. In the right figure, it is observed that the compensation achieves a centered spectrum.

Finally, the SAR image is shown in Figure 6 with a color map that black represents the highest power. In the upper image, the output of the FFT in range is shown while in the lower part, the output of the 2D matched filtering is shown. The azimuth profile of the vehicle is observed to be shorter in the unfocused image than the focused one. In addition, as the matched filtering is a low pass filter, the background noise is also suppressed.

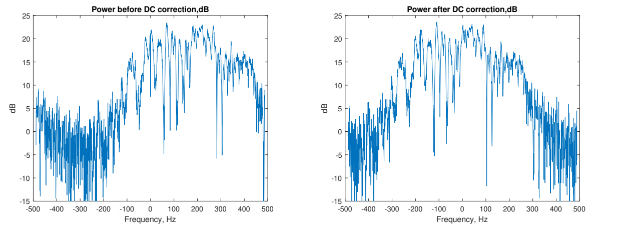

Fig. 5. Power spectrum of the signal. Left: Before DCF compensation, Right: After DCF compensation

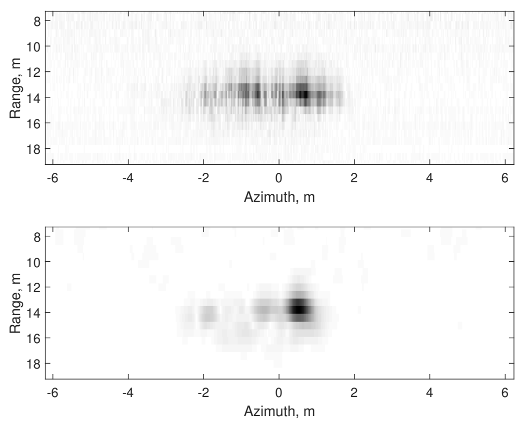

Fig. 6. SAR Image of the vehicle. Up: The fast time FFT of the received signal. Down: After the proposed method is applied

VII. Conclusion

In this work a multistatic FMCW ISAR imaging system is discussed. The proposed system is verified with the simulation and on site experiments. The results show that the proposed radar system is capable of not only range and velocity estimation but also generating the ISAR image. We emphasize that unlike the alternative sensors like cameras, inductive loops and LIDARs, a single side fire radar system is mostly sufficient to monitor a slice of the road without intruding the road. One disadvantage of the system is that a target closer to the radar may prevent to detect a target that is behind. However this performance degradation can be improved by installing the radar to a higher location. It is not easy to quantify the proposed method with the real data. That is why for the future works, a more under control traffic setup that includes moving reflectors can be designed for validation purpose.

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