High Resolution mmWave Radar by Radar Fusion and Sparse SAR

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***Abstract*—In automotive applications, mmWave radar has been limited to measuring the range of objects. Its limited role comes from two reasons: low resolution in three-dimensional (3D) imaging and blind spot from specularity. A single automotive radar typically has less than 5GHz bandwidth, and therefore its distance resolution is insufficient. By fusing multiple radars operating different frequencies, the total bandwidth of the radar system can be increased. Strong specular effects of mmWave signals cause incomplete or shabby radar images due to few reflected signals. We address the blind spot problem with random spatial sampling, resulting in the ability to reconstruct the radar image with missing reflected signals. Numerical results are used to prove the concept.**

***Index Terms*—FMCW radar; SAR; Compressive Sensing; Autonomous Vehicle.**

I. Introduction

Autonomous Vehicles (AVs) are no longer a dream, but a close reality. Google has been working on self-driving technology since 2009 and begun testing their prototype without a safety driver in 2017 [1]. Major automotive companies, such as Nissan, BMW, Ford, Tesla, GM, have already started testing their AVs and some of them announced a plan to develop commercial AVs in the consumer market by 2020. The recent progress in AVs has been achieved by the cutting-edge technology including advanced control theory, deep learning, sensor technology and so on. Among these advanced technologies, sensors that obtain 3D images of the environment are the first stage and one of the most important processes that enable autonomous driving. Even in today's non-autonomous vehicles, a number of sensors are implemented to assist the driver.

However, fully autonomous vehicles without any driver's intervention require some challenges to be cleared. In 2014, the Society of Automotive Engineers (SAE) published a standard that defines six different levels for vehicles from fully manual (Level-0) to fully automated system (Level-5) [2]. To achieve a Level-5 autonomous vehicle, the vehicle should perform all the driving functions under all roadway and environmental conditions that can be managed by a human driver. In current AVs' sensing system, optical sensors such as Light Detection And Ranging (LiDAR) and camera take a major role for 3D imaging. As both sensors operate at the optical wavelength, they can provide accurate perception in most scenarios. However, their sensing performance is significantly degraded in low visibility conditions such as fog, smog, and snow because the light is scattered before it arrives at the targets in such conditions [3].

In contrast to LiDAR and camera, radar can perform equally well in fog, smog, snow, and dark, as well as in sunny weather. A typical commercial LiDAR and radar system can achieve around 150m range detection and camera can do 300m in the sunny weather. While the camera visibility drops below 100m in the dark and the LiDAR below 50m in fog, smog, and snow, the radar can maintain almost the same performance in any conditions [4]. In recent years, the automotive industry has started to adapt mmWave radar whose wavelength is much shorter than the conventional radar. This advance provides the radar system a higher resolution image. In addition to the resolution benefits, the size of the radar system is shrunk by the shorter wavelength. With the compact size, forming an array of antenna is feasible and practical.

However, the role of mmWave radar has been limited to measuring the range of the objects in automotive application. Its limited role comes from two reasons: (1) low resolution in 3D imaging, (2) blind spot from specularity. A commercial LiDAR can offer 3D images with the distance accuracy of 2cm, the vertical resolution of 1 degree and the horizontal resolution of sub-degree [5]. On the other hand, the current commercial automotive mmWave radar typically provides the distance resolution of 5-70cm and the horizontal resolution of 7-15 degree, which is not accurate enough to perform the 3D imaging [6] [7]. Furthermore, mmWave signals experience mirror-like specular reflections causing only a few reflections back to the radar receiver. According to recent researches [8]–[10], 80% of the received power at 60-70GHz is carried by specular contribution rather than by scattering effects. This mirror-like characteristic can produce a blind spot of the radar image.

Indeed, mmWave radar is a great candidate to support LiDAR and camera in harsh driving conditions in AVs. However, we observe the following challenges that hamper the mmWave radar from producing high resolution imaging.

- The upper limit of the distance resolution of mmWave radar is no better than 3cm. In theory, the distance resolution depends on the bandwidth of the transmitted radar signal, i.e., a radar with wider bandwidth can give a higher distance resolution. However, a single automotive

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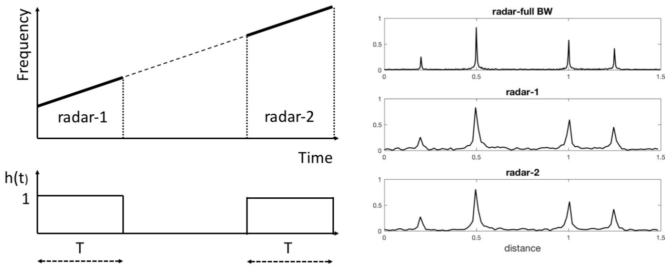
radar today typically has less than 5GHz bandwidth. The limited bandwidth comes from hardware constraints (antenna or front-end Radio Frequency (RF) devices). In order to cover the wider bandwidth in a single radar platform, its antenna should also support the wide bandwidth which brings other technical challenges [11] [12]. A wideband tunable RF device with low latency is also another requirement.
- The image acquired by mmWave radar can be either incomplete or shabby due to strong specular effects of mmWave signals. Because of the specular reflection, few or none of the reflected signals off the object head back to the radar.

We briefly outline our core approaches and research questions next.

- Radar fusion: We propose to use the existing radar platforms without any hardware modification and utilize them to collaborate with each other. By fusing the multi-radars over different operating frequencies, the combined information can be helpful to achieve a better resolution. However, new challenges emerge when fusing the multi-radars. (1) Simply concatenating the sample sets will lose the coherency between them, and therefore does not lead to improving the resolution. Preserving mutual coherence is required prior to processing further. (2) With the mutual coherence, the information is still missing in the frequency gaps between the multi-radars. Precise modeling of the missing gaps is a critical problem. (3) Adapting compressive sensing algorithm to reconstruct the missing information is not fully feasible in this scenario because the operating frequencies are not spread over randomly. As they are rather located in a specific frequency range, the performance of the compressive reconstruction will be compromised.
- Spatial diversity: In order to resolve the specularity in mmWave signals, we exploit spatial diversity. We observed that the specularity can give the radar a stronger reflection than the scattering when the radar locates at the right angle. By the mobility of automotive radar due to vehicles' movement, a synthetic aperture can be created. However, implementing Synthetic Aperture Radar (SAR) on vehicles has the following challenges. (1) Unlike airborne flight path whose velocity and trajectory are close to constant and linear, the vehicles create an irregular velocity and driving trajectory. (2) While the size of synthetic aperture in airborne objects can be extremely large, a much shorter aperture in the vehicle scenario may not be enough to resolve the specularity by itself.

The rest of the paper is organized as follows. Section II presents the proposed high resolution Frequency Modulated Continuous Wave (FMCW) radar system. Section III discusses the conclusions and future works.



(a) Truncated FMCW (b) Distance profile by FFT

Fig. 1. An example of fusing two radar systems is shown. (a) Two radar systems operating different bands. (b) Comparison of the resulting distance profiles.

II. High Resolution FMCW

A. Radar Fusion

The distance resolution of FMCW radar, Δd, is bounded by its bandwidth,

$$\Delta d = \frac{C}{2B} \tag{1}$$

where C is the speed of light, and B is the bandwidth of the FMCW radar. Increasing the bandwidth of radar, however, is not a simple task. RF devices that support the wide bandwidth are an expensive solution, especially to sweep the wide range in a short period. It is also a challenging problem to design a wideband antenna [11], [12]. Hence, it is urged to consider a new approach for this problem. Instead of increasing the bandwidth of a single radar, we propose to exploit the existing mmWave radar platforms (i.e., 24GHz, 60GHz, and 79GHz radars) without any hardware modification and utilize them to collaborate. By fusing the multiple radars over different frequencies, the combined information can be helpful to achieve a better resolution.

Consider an FMCW system with a full bandwidth that can achieve the desired distance resolution. Fig. 1 (a) shows an example of two sub-radar systems operating in two different frequencies. Each sub-radar system has a worse distance resolution than the one with the full bandwidth shown in Fig. 1 (b). For the sake of simplicity, we assume every radar has the same FMCW slope, α, and the same period of measurement, T. Then, the sub-radars can be viewed as a truncated FMCW system. The received signal for the full-bandwidth FMCW is

$$x_{full}(t) = \sum_{m=1}^{M} e^{j2\pi(\alpha\tau_m t + f_0\tau_m)}, t = nT_s, n = 0, ..., N-1 \tag{2}$$

where M is the number of reflectors, τ_m is the TOF of the m-th reflector, f_0 is the starting frequency of the FMCW, T_s is the sampling period, and N is the number of samples. Note that the frequency and the phase of the received signal are related to τ_m. Then, we can define a support function $h(t)$ as

$$h(t) = rect_T(t - t_1) + rect_T(t - t_2) \tag{3}$$

where $rect_T(t)$ is a rectangular function centered at 0 whose period is T, and amplitude is 1. The measured beat signal from the sub-radars is expressed by multiplying $h(t)$ and x_{full}:

$$x_{meas}(t) = h(t) \cdot x_{full}(t) + w(t). \tag{4}$$

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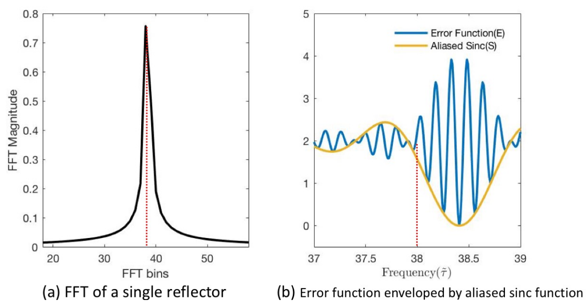

Fig. 2. (a) FFT magnitude of the measured beat signal reflected by a single reflector. (b) Error function.

where $w(t)$ is additive white Gaussian noise. The best estimate of τ_m would minimize the following error function:

$$E(\tilde{\boldsymbol{\tau}}) = \frac{1}{N}\sum_{n=0}^{N-1} ||x_{meas}(nT_s) - h(nT_s)\cdot\sum_{m=1}^{M} e^{j2\pi(\alpha\tilde{\tau_m}nT_s+f_0\tilde{\tau_m})}||^2,$$

where $\tilde{\boldsymbol{\tau}}$ is a M-length vector of $\tau_1,...,\tau_M$. However, the error function is not convex due to the complex exponentials. For further simplicity, consider a single τ and the frequency bands of the two radars are right next to each other, leading to a single rectangular function $h(t)$ with a full band period. The error function can be re-written as

$$\begin{aligned}E(\tilde{\tau}) &= \frac{1}{N}\sum_{n=0}^{N-1} ||e^{j2\pi(\alpha\tau nT_s+f_0\tau)} - e^{j2\pi(\alpha\tilde{\tau}nT_s+f_0\tilde{\tau})}||^2\\ &= 2-\frac{2}{N}\cos\left[2\pi\Big(f_0+\frac{\alpha(N-1)T_s}{2}\Big)(\tau-\tilde{\tau})\right]\\ &\cdot\frac{\sin\left[\pi\alpha NT_s(\tau-\tilde{\tau})\right]}{\sin\left[\pi\alpha T_s(\tau-\tilde{\tau})\right]}\end{aligned}$$

If one can find $\tilde{\tau}$ that satisfies the minimum value of the error function, the distance resolution can be improved better than $\frac{C}{2B}$.

The error function can be considered as an amplitude modulated signal with a carrier signal of frequency $f_0+(N-1)\alpha T_s/2$ enveloped by the aliased sinc function as shown in Fig. 2 (b). Note that the period of the carrier signal is dominated by the starting frequency f_0 (20-80GHz range) than the bandwidth term (below 5GHz), which results in multiple periods of the carrier signal in one FFT bin. Hence, gradient descent would not find the global optimum point due to many local minima in the search range. One can evaluate the error function by exhaustive search. The initial estimation of $\tilde{\tau}$ can be given by the location of the FFT peak (38th FFT bin) in Fig. 2 (a). However, finding the global minimum (38.4 in Fig. 2 (b)) requires a very fine step size due to high-frequency components from the carrier signal. The computation time will even worsen when there are multiple reflectors in a single FFT bin. Therefore, we propose to leverage the envelope instead of directly using the error function as a cost function. Because the envelope shares the minimum point with the original error function, one can find the same solution. The envelop signal varies slower and has fewer local minima, which will cause fewer difficulties to find the minimum value.

The description above assumes a single reflector and a smooth truncated FMCW system. Various research questions show up when these assumptions are not valid anymore. (1) The number of reflectors is usually unknown. An additional process to estimate the number of reflectors before solving the problem is required. (2) Multiple numbers of reflectors can be located within a single FFT bin. It will increase the number of variables to solve. Even with the single reflector assumption, an extremely fine step size is required due to the high-frequency component in the error function. (3) The truncated FMCW systems will have a frequency gap between them. It will make the error function complicated and challenging to solve.

B. Spatial Diversity

mmWave signals experience mirror-like reflections on the surface of the objects [8]–[10]. Because of the specular reflection, few or none of the reflected signals off the object can head back to the radar unlike the scattering effect (or diffuse reflection). The specular reflection becomes even more substantial on a smooth metallic surface, such as vehicles. The weak back-reflection due to specularity will produce an either incomplete or shabby image.

In order to resolve the specularity in mmWave signals, we exploit the spatial diversity of the vehicles. We observed that the specularity can give the radar a stronger reflection than the scattering when the radar locates at the right angle. In addition to resolving specularity, the spatial diversity can also help the radar improving its image. During the motion of the radar on a vehicle, the data is collected over time. The different geometric positions of the radar created by the motion of the radar produce a large synthetic aperture. In theory, a larger antenna aperture can produce a higher resolution.

The conventional SAR algorithms, such as Range-Doppler, utilize the phase-modulation effect of the echo signals and transform the spatial domain into the spatial frequency domain to resolve the locations of the objects. The Range-Doppler approach, however, is challenging to adapt non-uniform spatial sampling. In this paper, we consider a linear inverse-based SAR algorithm in order to incorporate random radar motion. SAR imaging can be viewed as a linear inverse problem in which the unknowns are the reflectivity map of the objects. A received signal at position u is linearly related to the unknowns as:

$$r_u(t) = \iint s(x,y)e^{j2\pi\left[\alpha\tau(x,y;u)t+f_0\tau(x,y;u)\right]}\,dx\,dy \quad (5)$$

where $s(x,y)$ is the reflectivity map at x and y. Note that τ is a function of x and y at given u. We can discretize x and y and vectorize $s(x,y)$ and obtain the following system equation at u:

$$\mathbf{r_u} = \mathbf{A_u}\mathbf{s} + \mathbf{w}, \quad (6)$$

where $\mathbf{s}$ is the vectorized $s(x,y)$, w is additive white Gaussian noise, and $\mathbf{A_u}$ is the matrix whose columns are the complex-exponential kernels in (5). By stacking the entire received

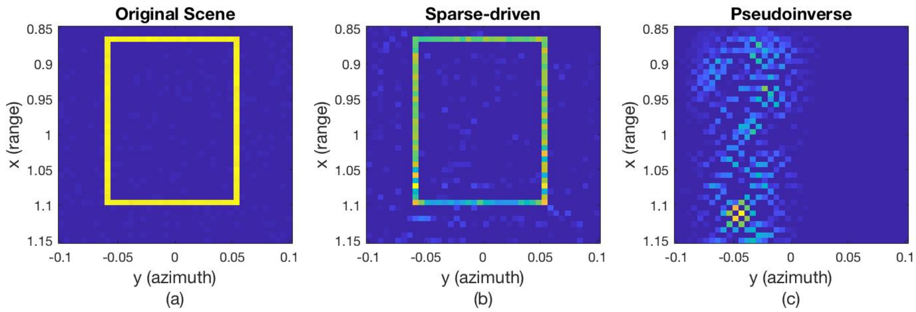

Fig. 3. SAR performance comparison by simulation : (a) original scene, (b) proposed sparse-driven SAR, and (c) conventional SAR by pseudo-inverse.

signal at all u, the entire system becomes $\mathbf{r} = \mathbf{A}\mathbf{s} + \mathbf{w}$. Given the limited number of measurements, the inverse problem can be ill-posed. We exploit the observation that the reflectivity map is sparse consisting of a small number of objects. Hence, the estimation of s can be obtained by

$$\min_{\mathbf{s}} \quad \frac{1}{2}\|\mathbf{r} - \mathbf{A}\mathbf{s}\|^2 + \lambda\|\mathbf{s}\|_1 \tag{7}$$

The choice of λ determines the relative contribution of the sparsity. Fig. 3 illustrates the simulation results of SAR images. By randomly taking 30% of the entire spatial samples, the reconstructed images by the sparse-driven SAR and by the pseudo-inverse are shown in Fig. 3(b) and (c), respectively.

While the sparse-driven SAR can reconstruct accurate SAR images with random radar positions, several research questions remain as the followings: (1) The target objects are assumed to be ideal scatters. Can we model the specularity and reconstruct the image? (2) The position of the radar has no error in the above simulation. When there exists noise in the measurement of the radar position, how can we adapt the errors? (3) In the practical scene, the targets are expected to be piecewise smooth, which is not modeled in the above model. Can we incorporate such smoothness in our model?

III. Conclusion and Future Work

The proposed research demonstrates how the performance of mmWave radar can be extended and provide autonomous vehicles with more reliable sensing capability. This research provides a new method for increasing the mmWave radar resolution by understanding the principles of electromagnetic (EM) radiation and the mathematical model of radar under dynamic vehicle motion.

- The proposed research will develop a model to combine multiple radar platforms and fuse the information in order to achieve better distance resolution. We will gain a better understanding of radar fusion and establish a framework to investigate the behavior of mmWave signals at different frequencies.
- The proposed research will investigate how the specularity of mmWave signal degrades the radar image. By understanding its specular behavior in vehicle situations, we will develop a new model for automotive radar imaging that resolves the specularity.
- The proposed research will incorporate the dynamics of vehicles in radar sensing/imaging. We will integrate the principles of EM radiation and the mathematical model of the radar in dynamic vehicle motion. This will provide a new algorithm for higher resolution radar images.

References

[1] A. J. Hawkins, "Waymo is first to put fully self-driving cars on US roads without a safety driver," https://www.theverge.com/2017/11/7/16615290/waymo-self-driving-safety-driver-chandler-autonomous, accessed: 2021-05-19.

[2] SAE On-Road Automated Vehicle Standards Committee and others, "Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles," *SAE International*, 2021, accessed: 2021-05-19.

[3] B. Yamauchi, "Fusing ultra-wideband radar and lidar for small ugv navigation in all-weather conditions," in *Int. Soc. Opt. Eng.(SPIE)*, vol. 7692, 2010, pp. 1–10.

[4] M. Barnard, "Tesla and Google Disagree About LIDAR? Which Is Right?" https://cleantechnica.com/2016/07/29/tesla-google-disagree-lidar-right/, 2016, accessed: 2021-05-19.

[5] Velodyne, http://velodynelidar.com/products.html, 2018, accessed: 2021-05-19.

[6] Bosch, "Radar-based driver assistance systems," https://www.bosch-mobility-solutions.com/media/global/products-and-services/passenger-cars-and-light-commercial-vehicles/driver-assistance-systems/predictive-emergency-braking-system/mid-range-radar-sensor-(mrr)/product-data-sheet-mid-range-radar-sensor-(mrr).pdf, 2018, accessed: 2021-05-19.

[7] J. Hasch *et al.*, "Millimeter-wave technology for automotive radar sensors in the 77 ghz frequency band," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 3, pp. 845–860, 2012.

[8] W. Fan, I. Carton, J. Ø. Nielsen, K. Olesen, and G. F. Pedersen, "Measured wideband characteristics of indoor channels at centimetric and millimetric bands," *EURASIP Journal on Wireless Communications and Networking*, vol. 2016, no. 1, p. 58, 2016.

[9] K. Haneda, J. Järveläinen, A. Karttunen, M. Kyrö, and J. Putkonen, "A statistical spatio-temporal radio channel model for large indoor environments at 60 and 70 ghz," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 6, pp. 2694–2704, 2015.

[10] F. Fuschini *et al.*, "Analysis of in-room mm-wave propagation: Directional channel measurements and ray tracing simulations," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 38, no. 6, pp. 727–744, 2017.

[11] P. S. Hall, P. Gardner, and A. Faraone, "Antenna requirements for software defined and cognitive radios," *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2262–2270, 2012.

[12] P. S. Hall *et al.*, "Reconfigurable antenna challenges for future radio systems," in *Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conference on*. IEEE, 2009, pp. 949–955.