High-Resolution Object Detection with SAR Imaging for Autonomous Driving

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ABSTRACT

The development of autonomous driving technology has been rapidly developing for the past decades. One key task in autonomous driving technology is the detection of objects around the vehicle. Radars are now more and more widely equipped by autonomous vehicles for object detection. In this paper, we present a novel approach of using on-board radars for high-resolution objection detection. Our approach is based on synthetic aperture radar (SAR). As the vehicle is moving, the position of the receiving antenna keeps changing, which allows the detection of objects at a higher accuracy. In this paper, the cross range resolution of the proposed detection system will be studied. The simulation and measurement data of the proposed multi-point observation scheme will be presented. It is shown that the method described in this paper can significantly improve the resolution of the object detection, and can be potentially useful in autonomous driving vehicles.

CCS CONCEPTS

• **Computing Methodologies**; • **Machine Learning**;

KEYWORDS

Autonomous driving, self-driving cars, synthetic aperture radar, remote sensing, object detection

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1 INTRODUCTION

The technologies in autonomous driving have evolved rapidly over the recent years, and now an extremely popular subject of discussion in today's scientific research field as well as in public media. The vehicles that drive themselves can save human beings from the tiring and time-consuming driving experience, reducing the traffic jams and collisions, as well as dramatically reducing the cost for transportation industry such as buses, taxies and interstate/intrastate cargo transportation [1-4]. However, the full autonomous driving is an extremely challenging task and has a long way to go [5]. According to the definition of the Society of Automotive Engineers (SAE), the autonomous driving systems are classified into levels 0 − 5, where Level 0 is defined as no automation and Level 5 is defined as full automation ("Steering wheel optional") [6]. Most of the commercialized autonomous driving systems nowadays are at the levels of 2 ("hands-off") to 3 ("eyes off"), while some experimental self-driving cars at Level 4 ("mind off") are being developed and tested.

High-resolution object detection is critical for autonomous driving vehicles [7-8]. The most recent self-driving cars are equipped with a variety of sensors, such as radar, sonar, Lidar, GPS, etc., to sense the environment around them. The application of radar systems in autonomous driving vehicles are more and more popular due to the consideration of the cost, effectiveness, and reliability. Synthetic aperture radar (SAR) has been a very important approach for imaging in an automotive scenario and has reached wide attention from researchers [9-10].

In this paper, we present a novel radar-based imaging system for autonomous driving vehicles. Our method includes a receiving antenna with multiple observation points, which operates in as synthetic aperture radar to detect the location of multiple targets. The methodology, as well as simulation and measurement data, will be presented. The proposed methodology is advantageous over prior methods for its significantly improved resolution and simple scheme.

2 METHODOLOGY

As the vehicle is moving, the radar equipped on the vehicles can observe at different physical locations, as shown in Figure 1. As long as the locations of the observation points are known, the radar will effectively operate as a synthetic aperture radar (SAR) [11], which can dramatically increase the resolution of the radar system by taking advantage of combining the measurement data at the different observation locations. Moreover, when the backscattered data from different receivers are combined, a better resolution is achieved in the azimuth direction.

Like any other measurements, the radar system needs to be calibrated to remove the systematic errors in the measurements such as uneven frequency responses of the VNA, the cables, and the antennas. One way to perform the calibration is to place an electrically large metallic plate exactly in front of the transceiver. For this scenario S_12 measurement is performed for each receiver and the frequency response is recorded. Since the reflection from the plate is significantly stronger than the leakage from the transmitting antenna to the receiving antennas, the recorded signal consists almost of the response of the antennas, cables and the free-space

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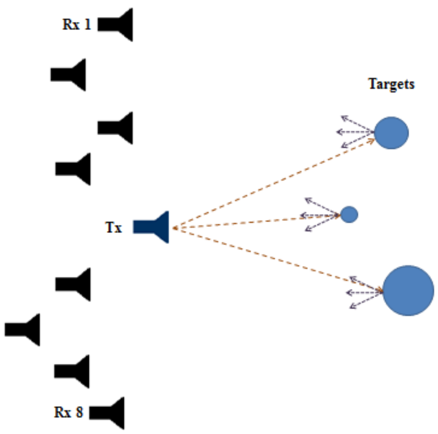

Figure 1: Target imaging with receivers at different positions.

path loss which would in turn allow us to factor out their effects in the final measurements. Moreover, time gating can be used to suppress the effect of multiple reflections and bounces from the surrounding environment.

As the locations and the received signal at the different locations are known, the mathematical formula of the target, S(r), can be derived as follows:

$$S(r) = \frac{1}{N_p N_f} \sum_{m=1}^{N_f} \sum_{n=1}^{N_p} E_{m,\ n,t,\ r} \tag{1}$$

Where

$$E_{m,\ n,t,\ r} = E_r^t(r_n, k_m)\, R_n(r_n, r)\, R(r_t, r)\, e^{jk_m R_n(r_n,r)} e^{jk_m R(r_t,r)} \tag{2}$$

And

$$R_n(r_n,\ r) = |r - r_n| \tag{3}$$

3 NUMERICAL SIMULATION

The method is numerically verified in Matlab simulation. In this simulation, the antenna is moved along the cross range axis. Two targets with different radar cross sections are placed at the same height as the receiving antennas.

Figure 2 shows the simulation results for a single target, sending a chirped signal from 1 GHz to 3 GHz. The receiving antennas are moved along the X-axis.

4 CROSS-RANGE RESOLUTION ANALYSIS

In the most general case of the imaging systems, the 3D location of the target is constructed by combining the received signal from different observation points. The range resolution is primarily defined by the bandwidths of the system whereas the cross range resolution (in this case both height and azimuth) are determined by the number of observation points in the cross-range direction. In other words, to enhance the resolution in height (in this case z), the number of observations should be increased in the height direction. The same also applies for the angular resolution.

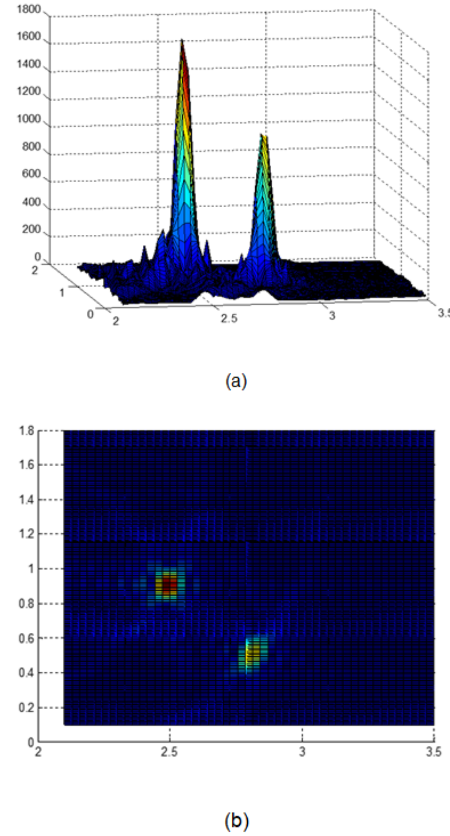

Figure 2: The detection of two targets with different radar cross sections. The receiving antenna is moved along the X-axis (cross-range). The frequency Bandwidth is 1 GHz-3 GHz.

In this study, we focus on the cross-range resolution, since it is important for a moving vehicle to accurately determine its distance to the obstacle in its moving direction.

where the receiving antenna is moved along the range (Y-axis) at a fixed X (cross-range), and a chirped signal from 1GHz to 3GHz is transmitted through the transmitter antenna. It can be seen from Figure 3 that although the antenna is placed at 20 different points along the range axis, the cross range position of the target is not detected. This confirms the need to move the antenna along the cross range to be able to detect the target accurately in the cross range.

As it has been shown before the relative position of the target is exactly determined in the x-y plane as the receiving antenna moves along both x and y directions. However, if the receiving antenna moves in the z-direction only, there would be ambiguity in the exact location of the target in the cross range direction, x, as shown in Figure 4. In conclusion, the cross range resolution is primarily defined by the number of observations and their displacement (relative to the wavelength) which is made in the same direction.

It needs to be mentioned that, although the target is not detected when the antenna is not moved along the X-axis (cross-range), by

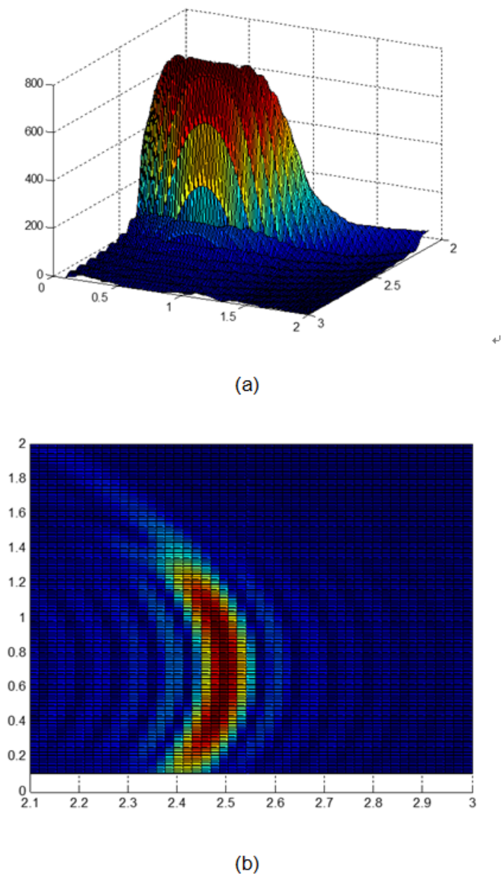

Figure 3: a: Single target detection, Bandwidth= 2 GHz, no sweep along the cross range axis, 20 sweeps along the range axis. b: Single targe t detection, Bandwidth = 2 GHz, no sweep along the cross range axis, 20 sweeps along the range axis (top view).

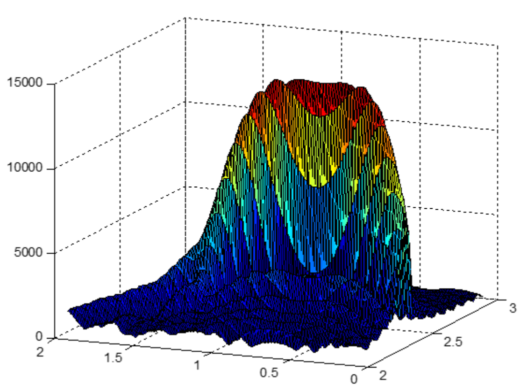

Figure 4: Single target detection, Bandwidth = 2 GHz, no sweep along the cross range axis, 20 sweeps along the range axis, 20 sweeps along the Z axis.

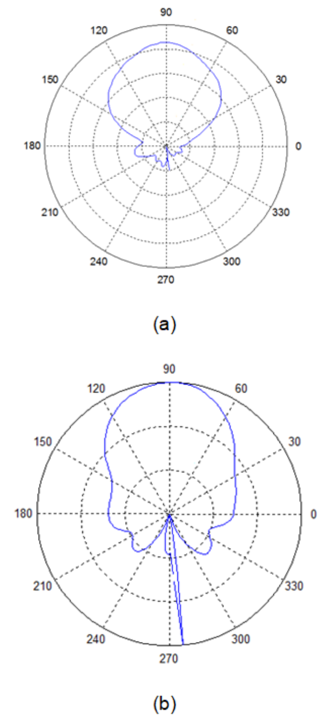

Figure 5: (a): The radiation pattern of the horn antennas in H plane. (b): Radiation pattern of the horn antennas in E plane.

sweeping along Z and only two rows along the cross range it is possible to find the target.

5 EXPERIMENTAL VERIFICATION

To emulate the case in self-driving cars, we experimentally tested the case with a single target with receiving antenna having a fixed Y position, while changing in 20X position.

A measurement platform is specifically developed for the test. A vector network analyzer is used to measure the received signal. Two ultra-wideband antennas are used as the transmitting and receiving antennas. The antennas are horn antennas designed to have an ultra-wide bandwidth of 1~18 GHz, and a gain of 6.3 dB at the boresight. HPBW is 40 degrees in the H plane and 30 degrees in the E plane. The antenna radiation patterns are designed to emulate the onboard radios on self-driving vehicles and are shown in Figure 5

The picture of the horn antenna is shown in Figure 6. It needs to be noted that, the reason we used horn antennas for the measurement is that its bandwidth is wide enough to cover the tested frequency band, and the radiation pattern can well emulate the radiation patterns of the onboard radars. Developing custom-designed on-board radars is not within the scope of this research.

The target is placed in a fixed position, while the receiving antenna is moved by a computer-controlled step motor, emulating the movement of the vehicle. Table I summarizes the measurement setup specifications. The measurement result is shown in Figure 7

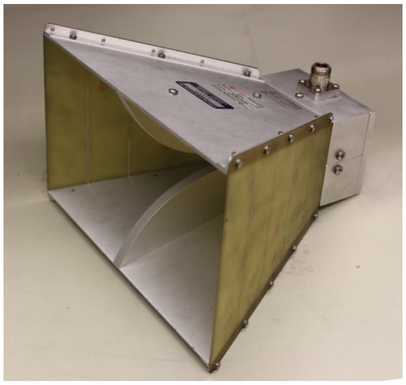

Figure 6: Single target detection, Bandwidth= 1 GHz, No sweep along the range axis.

Table 1: Measurement Setup Specifications for Scenario 1

Target Position	Fixed
Number of targets	1
Number of Points along the X axis	20
Number of Points along the Y axis	1
Number of Points along the Z axis	1
Frequency Bandwidth	1 GHz – 3 GHz
Number of Frequency Sampling Points	401

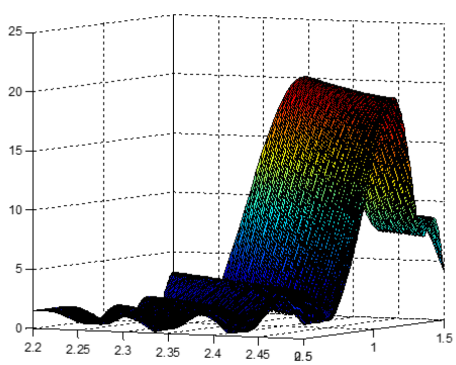

Figure 7: Single target detection, Bandwidth= 1 – 3 GHz, receiving antenna moves along the range axis.

In another test, two targets with almost equal radar cross sections were placed in front of the radar system. The resolution increases significantly when the number of observation points is increased to 40. The measurement result is shown in Figure 8. The measurement setup specifications are listed in Table 2

6 CONCLUSION

This paper studies the SAR-based high-resolution object detection methodology which can be used in autonomous driving vehicles.

Table 2: Measurement Setup Specifications for Scenario 2

Target Position	Fixed
Number of targets	2
Number of Points along the X axis	40
Number of Points along the Y axis	1
Number of Points along the Z axis	1
Frequency Bandwidth	1 GHz – 3 GHz
Number of Frequency Sampling Points	401

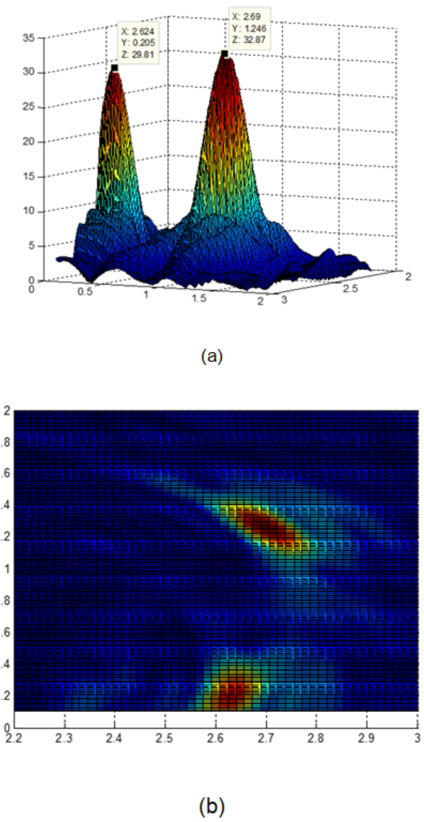

Figure 8: (a): Two targets detection, Bandwidth= 1 - 3 GHz, receiving antenna moves along the range axis. 40 sampling points. (b): Two targets detection, Bandwidth= 1 - 3 GHz, receiving antenna moves along the range axis. 40 sampling points. (top view)

It is shown that, by moving the receiving antenna and capture signal at different physical locations, the reception resolution can be significantly enhanced. As in practice, the vehicles will be moving, the methodology developed in this paper can be directly applied to the signal processing of radar signals captured by the vehicle's onboard radar.

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