Performance Evaluation of 24GHz FMCW Radar-based Blind-spot Detection and Lane-change Assistance under Dynamic Driving Conditions in a Vehicle Proving Ground

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***Abstract*—In this paper, an integrated mid-range automotive radar system with both Blind Spot Detection (BSD) and Lane Change Assistance (LCA) functions was developed. The system's maximum detection range was extended to 80m with an update time of 50ms or less. To assess the system's performance in real-world driving conditions, complex dynamic driving scenarios, including lane changing and lane following, in both straight and curved road environments were tested at an automotive proving ground. The developed integrated Blind-Spot Detection (BSD) and Lane Change Assistance (LCA) radar system was evaluated to determine its accuracy in detecting obstacles in the BSD and LCA regions and distinguishing true and false targets. The system demonstrated high probability of detection (Pd) of 94.4% and low false alarm rate (Fa) of 2.4%. BSD performance showed a Pd of 96.0% and 91.3% for constant velocity and longitudinal movement, respectively. LCA performance showed a Pd of 90% or higher and a Fa of 3% or less. The system was effective in enhancing road safety.**

Keywords— LCA, BSD, Intelligent Vehicle, Automotive Radar, Active Safety system, ROI pre-processing

I. INTRODUCTION

Driver-assistance systems play a crucial role in assisting drivers and preventing traffic accidents. Both the United States and European Union have recommended mandatory regulations for these systems and safety devices. One such system is blind-spot detection (BSD), which alerts the driver of vehicles in their blind spot, reducing the risk of collisions. Lane-change assistance (LCA) also informs the driver of approaching vehicles from behind, helping them to avoid accidents [1-5].

Radar-based BSD and LCA systems have been developed as they are less affected by weather and have longer detection distances compared to other sensors such as infrared, vision, and ultrasonic sensors. In this paper, we propose a low-complexity radar signal processing method based on the Region of Interest (ROI) preprocessing technique. This method reduces computation loads and allows for operation with a low-cost processor and low-size memory.

In our previous work [5], we presented the evaluation of the Blind Spot Detection (BSD) function of the integrated mid-range vehicle radar, with a focus on straight-ahead driving conditions. In this paper, we extend the evaluation to encompass complex dynamic driving scenarios, including lane changing and lane following, in both straight and curved road environments. The aim of this study is to thoroughly assess the performance of the integrated mid-range radar in various driving situations. In other words, we present a comprehensive evaluation of the performance of an integrated mid-range radar system designed for real-time Blind Spot Detection (BSD) and Lane Change Assistance (LCA) functions. To the best of our knowledge, there has been a lack of quantifiable evaluation of the performance of such radar systems under dynamic driving conditions. Hence, our aim is to fill this gap by conducting performance evaluations using several test scenarios in a dynamic driving environment at a proving ground.

Our proposed method offers a low-complexity solution for radar-based BSD and LCA systems, which can be implemented with a low-cost processor and low-size memory.

The rest of this paper is organized. In section II, the signal model of the FMCW radar are briefly explained. In section Ⅲ, we illustrate the development of the integrated BSD and LCA dual-function automotive radar system. In sections IV and Ⅴ, to evaluate the detection performance of the proposed BSD and LCA automotive radar, various test scenarios and corresponding experimental results at a proving ground and in dynamic driving environments are presented. Section Ⅵ concludes the paper.

II. FMCW SIGNAL MODEL

In the FMCW radar receiver, the reflected signal from the target, $r(t)$, and the conjugation of the FMCW transmitted signal, $s^{*}(t)$, are mixed. Following mixing the de-chirping signal is :

$$d_k(t) = r^{*}_k(t) \times s(t) \qquad (1)$$

where $d_k(t)$ indicates that the received signals $r_k(t)$ are transformed into sinusoidal form in the k-th antenna array. Through (1), it is derived that the transformed signals $d_k(t)$ have a sinusoidal waveform such that

$$d_k(t) = \sum_{m=0}^{M-1} a_m \exp\left(-j2\pi\mu\tau_m t\right)\exp\left(j2\pi f_{Dm} TN\right) \exp\left(j\pi k \sin\theta_m\right) + \omega_k(t) \qquad (2)$$

where d is assumed as $\lambda/2$ [5].

III. ROI Pre-processing Technique based Detection Scheme

We developed automotive BSD radar system based on Region of Interest (ROI) [6]. In this paper, we developed an integrated mid-range automotive radar system with both blind spot detection (BSD) and lane change assistance (LCA) functions based on ROI scheme. The conventional FMCW radar algorithm cannot be adopted for real time implementation due to their computational load for vehicle radar. We solve this complexity problem by the proposed low-complexity algorithm, which can satisfy the required specifications in vehicle radar. From (3), the time delay of the target is estimated from the indices of the periodogram of the received signal in the k-th antenna array. We define the DFT such that

$$D_k[p] = \sum_{n=0}^{N-1} d_k[n] e^{-j2\pi kn/N} \quad \text{for } p = 0,1,...,N-1 \qquad (3)$$

where p denotes an index of the discrete frequency for TOA. After the DFT processing in the first antenna array and the peak detection processing, we can obtain the range index matrix $\boldsymbol{I_t} = [I_0, I_1, \ldots I_{M-1}]$ of the targets.

Using the time index matrix $\boldsymbol{I_t} = [I_0, I_1, \ldots I_{M-1}]$ of the targets, the sequences $\boldsymbol{D_{Im}} = [D_0[I_m], D_1[I_m], \ldots, D_K[I_m]]^T$ for m-th target are established.

The simplified radar algorithms is used for the radar signal processing in the proposed system [7-8]. The DAC converts the beat signals into digitized signals which are stored into the internal and external RAM. Through a clipping operation, the transient beat signals due to the leakage between the transmitter and receiver channels are removed and only clean beat signals are extracted. The distances and velocities of the moving targets are obtained by means of a fast-chirp-based 2D-FFT algorithm [9-13]. Next, the beat signals are processed for range extraction by the first FFT, after which the range bin in the PRI direction is processed for Doppler extraction by the second FFT. To distinguish between the driving lane and another lanes, digital beam forming [14] is applied to extract the angles of the target vehicles. To extend the maximum detectable range to 80m, SNR performance is enhanced with the non-coherent integration by accumulating the multiple received beat signals. The digital beam forming processing is performed in the antenna direction for angle extraction. Finally, the targets are selected by adaptive thresholding based on the constant false alarm rate (CFAR) and maximum detection. The range, velocity, and angle of the detected targets are traced and maintained through Kalman filtering. The total processing time of the entire algorithm implemented in the integrated radar system is within approximately 50ms.

IV. Development of a Fast-Chirp-ROI-based Integrated Automotive Radars [5]

The parameters of the developed BSD and LCA automotive radar system as the following. The center frequency is set to 24GHz, and the bandwidth is set to 200MHz. The maximum detection ranges for BSD and LCA are 5m and 80m, respectively. The update time is less than 50ms.

The front-end module (FEM) for the integrated BSD and LCA automotive radar is depicted in Fig. 1. The FEM operates in the frequency range of 24.05GHz to 24.25GHz and uses frequency-modulated continuous-wave (FMCW) radar. The transmitter has an output power of 10dBm, and the transmission channel is shared by both BSD and LCA functions. The receiver channel uses two channels for LCA and one channel for BSD. During LCA operation, two channels are used for angle estimation, while one channel is used to determine the direction of a moving target during BSD operation.

The transmission antenna in the integrated radar system is composed of five element arrays and designed to simultaneously cover both BSD and LCA zones, with a field of view of 30 degrees for LCA detection and 120 degrees for BSD detection.

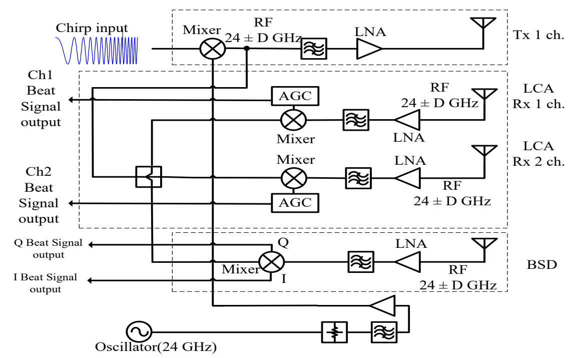


Fig. 1. Block diagram of the front-end module in the integrated BSD and LCA radar system

The BEM uses a TMS320 DSP processor, which offers low cost and high efficiency, making the integrated BSD and LCA radar system cost-effective. Additionally, the TMS320 model provides various interfaces including ADC, DMA, and CAN communication, as well as a high-performance signal processing library.

V. Performance of an Integrated Automotive Radar in Dynamic Driving Envrionments

Evaluation of the performance of the integrated radar system with BSD and LCA dual functions was conducted using a differential global positioning system (DGPS) with high accuracy on a high-speed circuit at an automotive proving ground in Daegu, Korea. The high-speed circuit was 3,681m long and consisted of one three-lane road with both linear and curved sections. Fig. 7 shows the test vehicle equipped with the integrated radar system and the target vehicle equipped with a DGPS system at the proving ground. To ensure accurate reference values between the two vehicles, a DGPS and an inertial navigation system with a velocity accuracy of 0.05 km/h were used. The measurement accuracy of the vehicle-to-vehicle range was less than 3cm and the communication coverage exceeded 1 km.

Seven test scenarios were used to evaluate the detection performance of the system, as follows:

Scenario 1. Target vehicle overtakes the test vehicle at a constant speed from the nearest lane

Scenario 2. Target vehicle passes the test vehicle at a constant speed in the second adjacent lane

Scenario 3. Target vehicle drives at a constant speed in the BSD zone

Fig. 2. The subject vehicle, the target vehicle, and measurement equipment

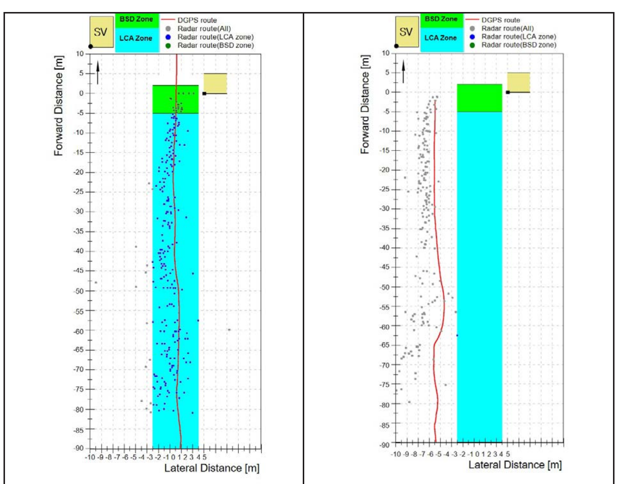
Scenario 4. Target vehicle drives under acceleration or deceleration in the BSD region

Scenario 5. Target vehicle drives in a lane-changing manner in the BSD area

Scenario 6. Target vehicle passes the test vehicle after changing lanes

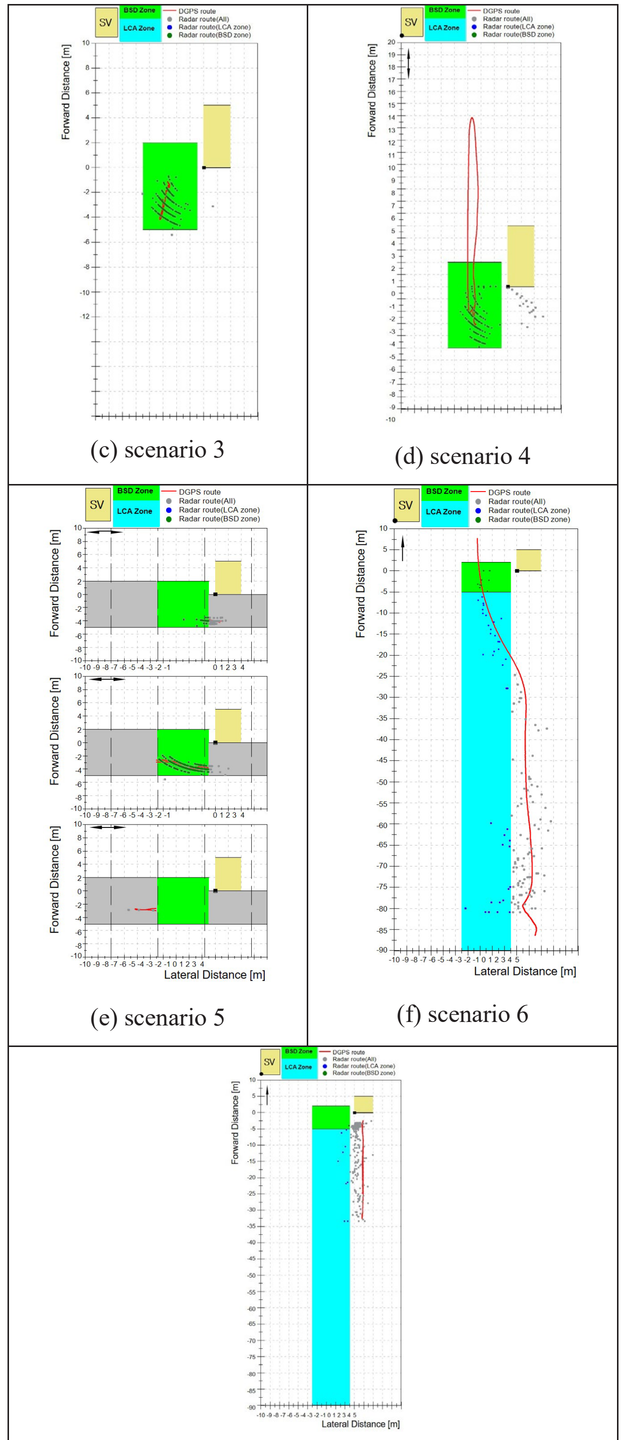
Scenario 7. Target vehicle travels at an accelerating or decelerating speed at the rear of the test vehicle.

In each scenario, the test vehicle was driven at a constant speed of 40 km/h in the third straight lane. The probability of detection and the false alarm rate of the target vehicle were measured. Figure 3 presents experimental results on the detection performance of the integrated radar system, as tested under the specified scenarios. The red line and black circles represent the target vehicle's travel path as measured by DGPS and the developed radar system, respectively. The blue and green circles denote the positions of the target vehicle in the LCA and BSD zones, respectively. The arrow in the top-left corner of each subfigure indicates the direction of the target vehicle's movement. The probability of detection is calculated as the number of targets detected in the BSD and LCA regions divided by the total number of targets.



(a) scenario 1

(b) scenario 2



(c) scenario 3

(d) scenario 4

(e) scenario 5

(f) scenario 6

(g) scenario 7

Fig. 3. Experimental results based on various dynamic driving scenarios

The detection performance of the developed integrated Blind-Spot Detection (BSD) and Lane Change Assistance (LCA) radar system was evaluated and the results are depicted in Figure 3. The probability of detection (Pd) and the false alarm rate (Fa) were calculated to determine the system's ability to accurately detect obstacles in the BSD and LCA regions and to distinguish between true and false targets.

As shown in Figures 3(a) and 3(b), the Pd of the integrated BSD and LCA radar system exceeded 94.4% with a detection of 1,178 out of 1,249 target vehicles and a Fa of less than 2.4% with 25 false detections out of 1,047 obstacles.

The performance of the BSD was further evaluated based on the movement of target vehicles at a constant velocity and in the longitudinal direction, as shown in Figures 3(c) and 3(d). The results show a Pd of 96.0% and 91.3% for constant velocity and longitudinal movement, respectively, with a detection of 1,755 out of 1,829 and 1,342 out of 1,470 target vehicles.

The LCA performance was evaluated based on the detection of target vehicles within a distance of 35m, as shown in Figures 3(e) and 3(f). The results show a Pd of 90% or higher and a Fa of 3% or less with a detection of 200 out of 209 target vehicles and 40 false detections out of 1,302 obstacles.

The developed integrated BSD and LCA radar system demonstrated excellent performance with high Pd and low Fa. These results validate the effectiveness of the system in enhancing road safety by accurately detecting obstacles in blind spots and assisting lane changes.

VI. Conclusions

In conclusion, we have developed an integrated short- and medium-range radar system for vehicles that utilizes both Blind Spot Detection (BSD) and Lane Change Assist (LCA) functions based on a real-time fast-chirp-based technique and ROI pre-processing. The system was tested in real-world driving conditions at an automotive proving ground, where performance evaluations were conducted using two driving scenarios. The results of these tests demonstrate the effectiveness of our radar system in detecting obstacles and providing accurate alarms in mixed operation driving conditions. The system utilizes reduced-size 2D-FFT and digital beam-forming algorithms for signal processing and has the potential to improve safety for drivers on the road. The developed integrated Blind-Spot Detection (BSD) and Lane Change Assistance (LCA) radar system was evaluated to determine its accuracy in detecting obstacles and distinguishing between true and false targets as the probability of detection (Pd) and false alarm rate (Fa). The system demonstrated excellent performance, with a Pd exceeding 94.4% and a Fa of less than 2.4%. The BSD performance was evaluated based on the movement of target vehicles at constant velocity and in the longitudinal direction, with a Pd of 96.0% and 91.3% respectively. The LCA performance was evaluated based on the detection of target vehicles within 35m, with a Pd of 90% or higher and a Fa of 3% or less. These results validate the effectiveness of the system in enhancing road safety.

Acknowledgment

This research was partially supported by DGIST R&D Program of the Ministry of Science, ICT and Future Planning, Korea (23-IT-01), and was partially supported by the Korea Institute for Advancement of Technology (KIAT) and funded by the Ministry of Trade, Industry and Energy (MOTIE) of the Korean Government (No. P0018599).

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