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2D FFT ROI를 이용한 중단거리 차량용 레이더의 성능 시험 및 평가+

(Experimental Test and Performance Evaluation of Mid-Range Automotive Radar Systems Using 2D FFT ROI)

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요 약 본 논문은 ISO 17387규격에서 제공하고 있는 차선변경 보조시스템(LCDAS)에 기반을 둔 중단거리 차량용 레이더 시스템을 개발하였다. 사용한 규격에서는 지능형 이동 시스템에서 사용하고 있는 성능 요구사항과 시험 과정에 대해 기술되어 있다. 중단거리 차량용 레이더 시스템은 최대 80m까지 목표물을 검출할 수 있으며, 갱신주기는 50ms로 단축할 수 있도록 설계하였다. 또한, ROI 전처리 기술을 활용하여 신호처리에서의 계산량을 대폭 감소시킬 수 있었다. 최종적으로, 실제 운전 상황을 설정하여 실제 시험을 수행하였으며, 두 가지의 시나리오를 설정하여 성능을 평가했다.

핵심주제어: 차량용 레이더, 차선변경보조시스템, BSD, LCA, ISO 17387, ROI

Abstract In this paper, we developed a mid-range automotive radar systems based on the performance requirements and test procedures of the intelligent transport systems, that is lane change decision aid systems (LCDAS). The mid-range automotive radar has the maximum detection range up to 80m and an update time within 50ms. The computational loads of a signal processing were reduced by using ROI preprocessing technique. Considering actual driving environments, radar performance evaluations were conducted in two driving scenarios at an automotive proving ground.

Keywords: Automotive Radar, LCDAS, BSD, LCA, ISO 17387, ROI

1. Introduction

Currently, driver-assistance systems play an important role in assisting drivers in their judgements and preventing traffic accidents in many cases. The United States and European Union have recommended the mandatory regulation of driver-assistance systems and safety devices. Among the many safety systems, blind-spot detection (BSD) provides the driver with protection against collisions by

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detecting vehicles in the blind spot and signaling the driver (Barton, 1980; BS., 2008). Moreover, lane- change assistance (LCA) informs the driver of the positions of other vehicles at longer distances, helping the driver to avoid accidents with vehicles approaching from behind. Previously, BSD and LCA systems have been implemented by infrared, vision, and ultrasonic sensors. And these sensors are very sensitive to weather or have shorter detection distances. However, radar-based BSD and LCA systems have developed because the radar systems are less sensitive to weather and have longer detection distances (Ju et al., 2014; Jin et al., 2016).

Radar-based Lane Change Assistance (LCA) systems are utilized in autonomous vehicles to enhance road safety by aiding drivers in making safe lane changes. The key components of these systems are as following.

A radar sensor is installed on the vehicle to detect the presence of other vehicles in the vicinity. The radar sends out a continuous wave or a pulsed wave and measures the reflection of the wave to calculate the target vehicle's distance, velocity, and direction.

The radar data processing is operated by using various algorithms such as Fast Fourier Transform (FFT), matched filtering, and constant false alarm rate (CFAR) to detect target vehicles and differentiate them from other objects like road signs and buildings.

Finally, the processed radar data is used to make decisions about lane change assistance (Lane Change Decision-Making). The system evaluates the target vehicle's relative position, velocity, and distance to determine if a lane change is safe.

(1) Advantages:

High Accuracy: The radar-based LCA system provides high accuracy in detecting target vehicles and calculating their relative position, velocity, and distance.

All-Weather Capability: The system can function in all weather conditions including rain, fog, and snow, where cameras and other optical sensors may not be efficient.

Long-Range Detection: The radar-based LCA system has a longer detection range compared to cameras and other optical sensors, enabling early warnings of potential lane change conflicts.

(2) Disadvantages:

Cost: The cost of the radar-based LCA system is higher compared to camera-based systems.

Complexity: The processing algorithms required for the radar-based LCA system are more complex than camera-based systems, which may result in increased system complexity and reduced reliability.

(3) Characteristics:

Non-Invasive: The radar-based LCA system is non-invasive, meaning it does not disturb the target vehicles or the road environment.

Real-Time Processing: The algorithms used in the system are designed for real-time processing, providing quick and accurate lane change decisions.

Low False Alarm Rate: The algorithms used in the system are designed to minimize the false alarm rate, reducing the risk of false lane change warnings.

To improve computation load and hardware constraints in Radar-based Lane Change Assistance (LCA) systems, several methods have been investigated. Some of them include algorithm optimization and data reduction.

One scheme is a method of more efficient algorithms to reduce the computation load and hardware requirements. For example, using low-complexity algorithms for parameter estimation (Khodjaev et al., 2014; Kim et al., 2017; Kim et al., 2018), target detection(Hyun et al., 2015) and target tracking, and data association (Hyun et al., 2016).

The other technique is utilized by 1D Region of Interest (ROI) pre-processing scheme to reduce the data before processing for reducing the memory requirements (Ju et al., 2014; Jin et al., 2016; Hyun et al., 2017). These were demonstrated in a laboratory setting.

In this paper, we propose a new 2D ROI-based mid-range automotive radar that combines both Lane Change Assistance (LCA) and Blind Spot Detection (BSD) functions. This is an improvement over the conventional 1D ROI-based target detection method, as it balances the demands of data size and performance. By implementing these techniques, it is possible to improve the computation load and hardware constraints in Radar-based Lane Change Assistance (LCA) systems.

Thus, we can develope more robust target-detection algorithms. The mid-range radar systems have a maximum detection range up to 80m.

In this paper, we propose low-complexity radar signal processing based on 2D ROI(Region of Interest) preprocessing technique to reduce the computation loads. The 2D ROI preprocessing makes to operate with a low cost processor and low-size memory. And we can evaluate the detection performance for two test scenarios considering an actual road environment at a proving ground(PG). According to the ISO 17387 standard, the performances of the BSD and LCA can be confirmed in actual driving test sites.

This paper is organized as following. In section 2, the mid-range radar systems are briefly explained. Section 3 describes the ROI preprocessing based detection scheme for BSD and LCA function. In sections 4, two test scenarios and actual driving test results are presented. Finally, in section 5, we conclude.

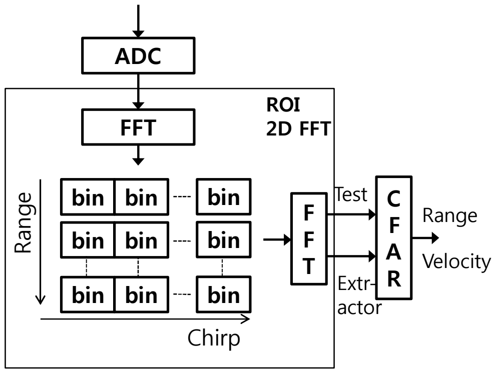

Fig. 1 Block diagram of the 2D FFT ROI radar system

2. Mid-range Automotive radar systems

Fig. 1 shows a schematic block diagram for the mid-range automotive radar supporting for the BSD and LCA dual functions.

2.1 Transmitter

The transmitted FMCW chirp signal is expressed as follows:

$$s(t) = \begin{cases} a\exp\left(j2\pi(f_c t + \frac{\mu}{2}t^2) \right) & \text{for } 0 \le t < T \\ 0 & \text{elsewhere} \end{cases} \quad (1)$$

where f_c is the carrier frequency, a and μ are the complex amplitude and the rate of change of the instantaneous frequency of a chirp signal and T is the duration of a FMCW chirp signal.

2.2 Receiver

We consider M targets receiving at k antenna arrays. Let ϕ_m, τ_m, and f_{Dm} denote the angle, delay, and Doppler frequency due to velocity of the m-th moving target. The received signal at k-th antenna array for N-th chirp can be represented by

$$r_k(t) = \sum_{m=0}^{M-1} a_m s(t-\tau_m)\exp(j2\pi f_{Dm}TN)\exp(j\frac{2\pi}{\lambda}dk\sin\theta_m) + \omega_k(t) \quad (2)$$

where a_m and λ denote the complex amplitude, and wavelength of the carrier signal, respectively. Also, d is the spacing between the adjacent antenna elements. $\omega_k(t)$ is the additive white Gaussian noise (AWGN) signal. In the FMCW radar receiver, the reflected signal from the target, $r(t)$, and the conjugation of the transmitted signal, $s^*(t)$, are mixed. Following the mixing, the output signal is

$$d_k^{mixer}(t) = r_k(t) \times s^*(t) \quad (3)$$

Through de-chirping and filtering out, the signal $d_k(t)$ is as follows:

$$d_k(t) = \sum_{m=0}^{M-1} a_m \exp(-j2\pi\mu\tau_m t)\exp(j2\pi f_{Dm}TN) \exp(j\pi k\sin\theta_m) + \omega_k(t) \quad (4)$$

where d is assumed as $\lambda/2$. It indicates that the received signals $r_k(t)$ are transformed into sinusoidal form in the k-th antenna array and the de-chirping signals $d_k(t)$ have any sinusoidal waveform.

3. ROI pre-processing

We developed automotive BSD radar system based on Region of Interest (ROI) preprocessing scheme (Hyun et al., 2017). The mid-range automotive radar system has both blind spot detection (BSD) and lane change assistance (LCA) functions. The complexity of FMCW radar algorithm has to be improved for real time radar implementation on a cost-effective embedded processor.

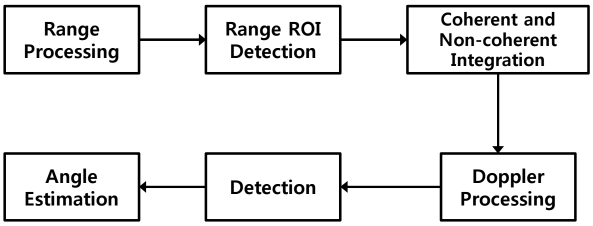

Fig. 2 Simplified radar algorithm of the BSD and LCA

The de-chirping signal is applied by the DFT operator such that

$$D_k[p] = \sum_{n=0}^{N-1} d_k[n]e^{-j2\pi kn/N} \text{ for } p = 0,1,\ldots,N-1 \quad (5)$$

where p denotes an index of the frequency. From (5), the time delay of the target is estimated from the indices of the periodogram of the received signal in the k-th antenna array.

Fig. 2 shows the simplified radar system used for the radar signal processing in the proposed system (Ju et al., 2014; Jin et al., 2016). The distances and velocities of the moving targets are obtained by means of a fast-chirp-based 2D-FFT algorithm (Khodjaev et al., 2014; Hyun et al., 2015; Hyun et al., 2016; Kim et al., 2017; Kim et al., 2018). However, the proposed algorithm performs FFT operation only for M range bins corresponding to moving targets, so that we can reduce the computation load. 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. The range bin equals to the number of target M and $M << N$ (the point of FFT N) generally. To distinguish between the driving lane and another lanes, digital beam forming (Barton, 1980) is applied to extract the angles of the target vehicles. The digital beam forming processing is performed in the antenna direction for angle extraction. Finally, the targets are selected by adaptive threshold based on the constant false alarm rate (CFAR) and maximum detection.

Table 1 Specifications of the BSD and LCA

Center Frequency	24GHz
Bandwith	200MHz
Modulation scheme	FMCW
Detection range	BSD: 5m LCA: 80m
Field of view(FoV)	LCA: 30 deg. BSD: 120 deg.
Relative velocity	-70 ~ 70m/s
Update time	50ms
Number of Tx/Rx Antenna	Tx: 1 RX: 3
Sampling rate	5MHz
Chirp rate	50us
Range Resolution	0.45m

4. Experimental Test and Performance Evaluation

4.1 System parameters

Table I shows the parameters of the developed BSD and LCA automotive radar system. 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.

4.2 Performance evaluation

In order to evaluate the detection performance of the developed integrated radar including BSD and LCA dual functions, performance tests were conducted using DGPS (differential global positioning system) with very high accuracy along a high-speed main circuit at an automotive proving ground in Daegu, Korea. The high-speed circuit has a total length of 3,681m with one three-lane road consisting of a linear section and a curved section.

Fig. 3 The subject vehicle, the target vehicle.

Fig. 3 shows the subject vehicle equipped with the developed integrated radar and the target vehicle with the installed GPS system at a proving ground. For accurate reference values between the target and the radar system, the velocity accuracy is within 0.05 km/h. The range accuracy is less than 3cm and the communication coverage exceeds 1 km. The DGPS system is installed at the center of the target vehicle. The dimensions of the target vehicle are 1,855mm (width) by 4,525mm (length) and those of subject vehicle are 1,920mm (width) and 5,125mm (length).

In this paper, we use the 2D ROI(Region of Interest) preprocessing technique to reduce the computation loads. The 2D ROI preprocessing makes to operate with a low cost processor and

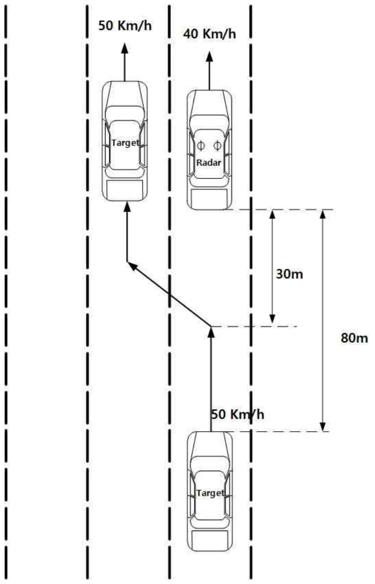

Fig. 4 Scenario 1 (BSD & LCA Test)

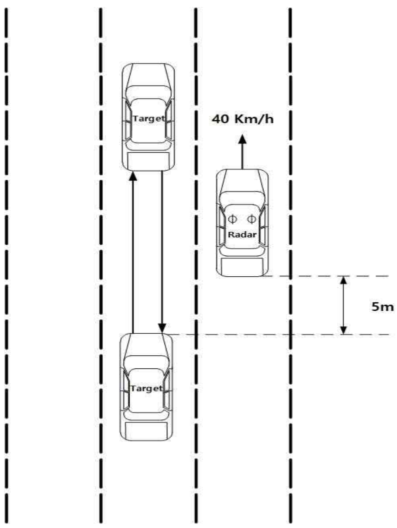

Fig. 5 Scenario 2 (LCA Test)

low-size memory.

The test scenario consists of two typical cases to evaluate the detection performance. These are described below.

Scenario 1. The target vehicle was driven at a speed of 50km/h at a distance of 80 m or more from the rear of the subject vehicle

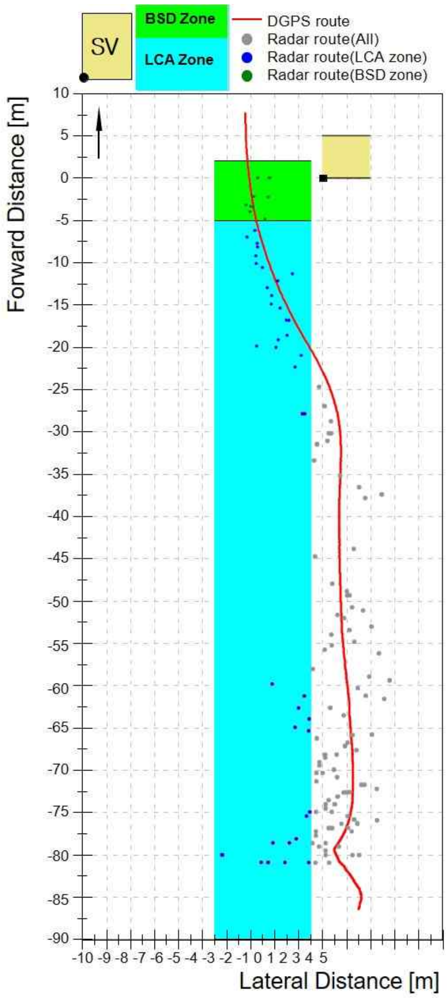

Fig. 6 Actual experimental results according to Scenario 1

on the third straight lane. And, when the target vehicle reached 30m from the rear of the subject vehicle, it changed to the second lane and overtook the subject vehicle.

Scenario 2. The target vehicle moved longitudinally from 5m to 30m from the back of the test vehicle in the first straight lane.

Here, scenario 1 in Fig. 4 is an experiment to evaluate whether the radar system can detect the target within the BSD and LCA zone and then present an alarm when the

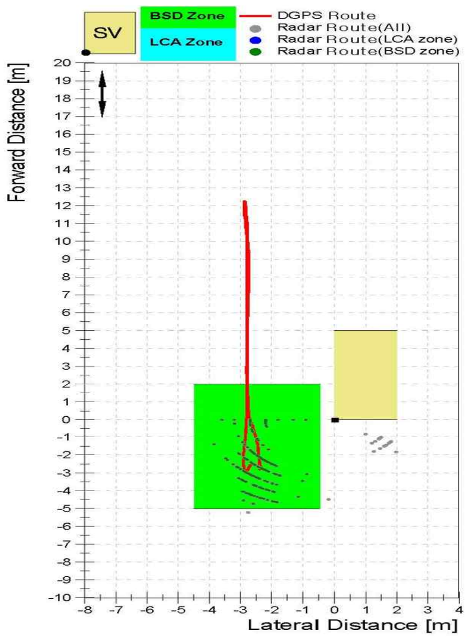

Fig. 7 Actual experimental results according to Scenario 2

alarm must be given. Scenario 2 in Fig. 5 is conducted to determine whether the radar detects obstacles existing outside the BSD and LCA zone and to ensure that unnecessary alarms are not given. The probability of detection and the false alarm rate of the target vehicle were measured.

As shown in Fig. 6 and 7, the detection performance of the developed integrated BSD and LCA radar system was evaluated. The color of dots indicates the decision of radar: all zone, LCA zone, and BSD zone. route The probability of detection and the false alarm rate are shown. That is, how often obstacles existing in the BSD and LCA regions can be detected as target vehicles and obstacles existing outside the BSD and LCA regions not as target vehicles were determined. The probability of detection and the false alarm rate of the integrated BSD and LCA radar system are both important performance factors. In Figs. 6 and 7, the LCA experimental results show a probability of detection of 90% or more and a false alarm rate of 3% or less within a distance of 35m as the system accurately detected 200 target vehicles out of 209 vehicles and incorrectly detected 40 target vehicles out of 1,302 vehicles.

5. Conclusion

In this paper, we developed a real-time fast-chirp-based automotive radar system having BSD and LCA functions based on 2D ROI pre-processing technique. Radar signal processing is carried out using reduced-size 2D-FFT and digital beam-forming algorithms. The radar is tested in an actual driving road test site. Two driving test scenarios are constructed and performance evaluations were conducted at an automotive proving ground.

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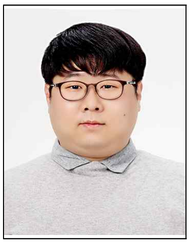

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