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ISRSS: INTEGRATED SIDE/REAR SAFETY SYSTEM

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ABSTRACT−As driver assistant systems (DAS) and active safety vehicles (ASV) with various functions become popular, it is not uncommon for multiple systems to be installed on a vehicle. If each function uses its own sensors and processing unit, it will make installation difficult and raise the cost of the vehicle. As a countermeasure, research integrating multiple functions into a single system has been pursued and is expected to make installation easier, decrease power consumption, and reduce vehicle pricing. This paper proposes a novel side/rear safety system using only one scanning laser radar, which is installed in the rear corner of the driver's side. Our proposed system, ISRSS (integrated side/rear safety system), integrates and implements four system functions: BSD (blind spot detection), RCWS (rear collision warning system), semi-automatic perpendicular parking, and semi-automatic parallel parking. BSD and RCWS, which operate while the vehicle is running, share a common signal processing result. The target position designation for perpendicular parking and parallel parking situations is based on the same signal processing. Furthermore, as system functions during running and those during automatic parking operate in exclusive situations, they can share common sensors and processing units efficiently. BSD and RCWS system functions were proved with 13025 and 2319 frames, respectively. The target position designation for perpendicular and parallel parking situations was evaluated with 112 and 52 situations and shows a success rate of 98.2% and 92.3%, respectively.

KEY WORDS : Active safety vehicle, Blind spot detection, Parking assist system, Rear collision warning, Scanning laser radar

1. INTRODUCTION

As driver assistant systems (DAS) and active safety vehicles (ASV) with various functions become popular, it is often the case that multiple systems are installed on a vehicle. If each function uses its own sensors and processing unit, then installation is difficult, and the vehicle price will increase (Morton, 2007a, 2007b). As a countermeasure, research integrating multiple functions into a single system has been pursued and is expected to make installation easier, decrease power consumption, and lower the vehicle price (Schulz and Fürstenberg, 2006; Takahashi *et al.*, 2002; Akita *et al.*, 2006). Such an approach can be divided into two categories: cases incorporating multiple system functions by implementing one signal processing (Schulz and Fürstenberg, 2006) and cases implementing multiple system functions operating in exclusive situations in a single system (Takahashi *et al.*, 2002; Akita *et al.*, 2006).

By installing one ALASCA XT scanning laser radar on the front-side of a passenger vehicle, IBEO demonstrated a system implementing seven system functions: lane departure warning (LDW), automatic emergency braking, adaptive cruise control (ACC) stop and go, pedestrian protection, low speed collision avoidance, traffic jam assistant, and pre-crash (Schulz and Fürstenberg, 2006). For a truck, they installed one ALASCA XT scanning laser radar at the front corner of the passenger side to implement seven system functions: turning assist, LDW, cut-in assist, slow moving assist, automatic emergency braking, traffic jam assist, and stop and go assist (Schulz and Fürstenberg, 2006). Because all system functions, except LDW, are based on range data detection and processing, the suggestions from IBEO are expected to reduce the number of sensors and the required processing power drastically.

Using a single sensor for multiple system functions in exclusive situations would make it possible to build a system implementing multiple system functions without increasing the number of sensors or the processing power required. Toyota and Aisin Seiki implemented LDW with a wide-angle camera installed for parking assistance at the back end of the vehicle (Takahashi *et al.*, 2002). In addition, Aisin Seiki implemented rear collision warning (RCW) with the same camera (Akita *et al.*, 2006). In this case, because the rearward camera installed for parking assistance can be used for LDW and RCW, multiple system functions share both the sensor and processing unit.

Until recently, a number of problems have remained concerning scanning laser radars: 1) scanning laser radars

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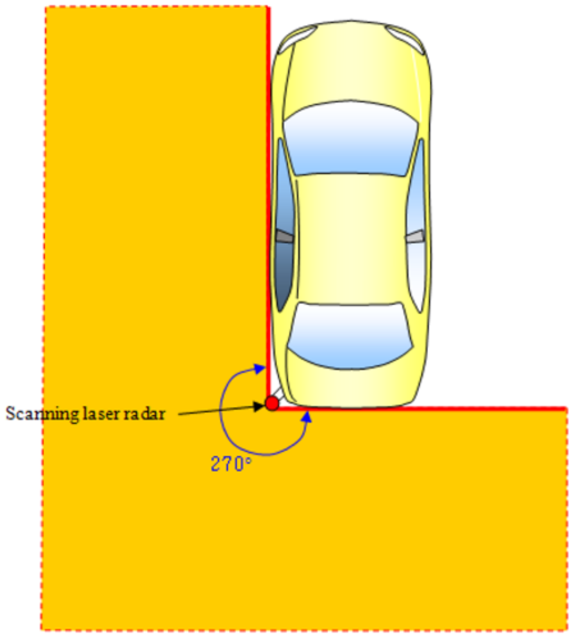


Figure 1. Sensor installation and coverage.

that are more robust to fog and rain should be developed, 2) their size should be reduced so that they can be integrated into the bumper, and 3) the endurance requirement for automotive application, which has been open to question because of its mechanical scanning mechanism, should be satisfied. Assuming these problems can be solved thanks to recent progress (Morton, 2007a, 2007b; Schulz and Fürstenberg, 2006) in the near future, we propose a novel side/rear safety system using only one scanning laser radar, and which is installed at the driver's side rear corner as shown in Figure 1 (Jung *et al.*, 2007a). The installed scanning laser radar monitors objects in the range of 270° from the driver's side to the rear.

Our proposed system, the ISRSS (integrated side/rear safety system), integrates and implements four system functions: BSD (blind spot detection), RCWS (rear collision warning system), semi-automatic perpendicular parking, and semi-automatic parallel parking. ISRSS consists of four components: scanning laser radar, ECU (electronic control unit), active steering system, and user interface. In particular, our previous work (Jung *et al.*, 2008a) indicated that target parking position for perpendicular parking situations could be established reliably using a single scanning laser radar. BSD and RCWS operating while the subjective vehicle is running share a common signal processing result. The target position designation for perpendicular parking and parallel parking situations are based on the same signal processing. Furthermore, as system functions during running and those during automatic parking operate in exclusive situations, they can share common sensors and processing units efficiently. Such efficiency could be verified by comparing the case of LATERAL SAFE (Amditis *et al.*, 2008). One long range radar unit, several units of short range radar, two cameras, and processing units for each system function are installed for three system functions: lateral and rear area monitoring, lateral collision warning, and lane change aid.

This paper explains the recognition methods for four system functions of the proposed ISRSS and provides performance evaluation results. We insist that the proposed ISRSS is superior to an implementation with separate systems from the point of view of performance and price. Chapter II provides a brief survey for each of the four system functions. Chapter III explains the methods monitoring the dangers from the side/rear direction when the vehicle is running, and Chapter IV details target position designation methods for perpendicular and parallel parking situations. In particular, whereas the same method used for perpendicular parking situations was applied to parallel parking situations without significant change in our previous work (Jung *et al.*, 2007a), this paper will explain problems associated with the previous method and will propose a novel method to rectify those problems. In Chapter V, experimental results and quantitative evaluations for each system function are provided, and in Chapter VI a conclusion is given.

2. SURVEY OF FOUR SYSTEM FUNCTIONS

2.1. Blind Spot Detection

A blind spot is defined as an area that a driver cannot monitor by simply turning his/her head or by using the side mirror, and thus any vehicle in this area poses a potential danger to the subject vehicle. According to W. Scott Pyle, each year more than 826,000 vehicles in North America are involved in lane-change-side blind-spot accidents. Including Western Europe and Japan, this accident type rises to include more than one million vehicles annually (Pyle, 2008). There are two noticeable statistics involving lane change accidents: 1) 78% of all lane change accidents are characterized by the vehicle entering the new lane deliberately, with the driver unaware of the hazard nature of the new lane, and 2) in 65% of accidents, the vehicle enters the lane and collides with another vehicle at or about the same speed. Considering these facts, a system detecting an adjacent vehicle in the blind spot and warning the driver attempting a lane-change will apparently reduce the number of accidents that would otherwise occur. BSD has been developed to implement such system function, and its implementation could be divided into three categories according to detection method: active sensor-based, passive sensor-based, and communication-based.

Active sensors for BSD include SRR (Pyle, 2008; SIEMENS VDO, 2008; Pudenz, 2007), near infra-red (NIR) beam-based distance sensors (Trico Electronics, 2008), and ultrasonic sensors (Song *et al.*, 2004; Chan Yet and Oidwai, 2005; Cho *et al.*, 2008). SIEMENS VDO used a 24-GHz dual-beam radar sensor (SIEMENS VDO, 2008), and Mercedes-Benz S and CL-class used a sensor network consisting of six SRRs (Pudenz, 2007). Valeo Raytheon Systems (VRS) lane change assistance (LCA) uses sophisticated phased array radar technology to sweep continually from the front to the rear portion of the zone. VRS LCA significantly reduced the possibility of false positives by detecting whether the adjacent vehicle was moving from back to front (Pyle, 2008). Trico Electronics implemented BSD using the NIR beam-based distance sensor (Trico Electronics, 2008). The detection zones are created by beams of infrared lasers, which can be custom configured through software parameters; the number of beams is 6~7. Song *et al.*(2004) and Chan Yet and Oidwai (2005) showed that multiple ultrasonic sensors installed on the side surface of the subjective vehicle could detect an adjacent vehicle and Youngha Cho *et al.* (2008) showed that one wide-angle ultrasonic sensor installed at the side-rear corner implemented BSD in urban situations.

The passive sensor for BSD includes both the far infrared (FIR) sensor and visible range vision sensor. To detect a vehicle in the BSD zone using the fact that the front side of a running vehicle was hot, Delphi installed FIR sensor cable to sense a temperature change at the rear corner (Delphi, 2008). Almost every vision-based method utilizes optical flow, and they can be divided into three categories according to tracking target: based on the motion prediction of the ground surface (Batavia *et al.*, 1997; Wang *et al.*, 2005), grouping of optical flow caused by an approaching vehicle (Techmer, 2004, 2001; Tan *et al.*, 2006; Díaz *et al.*, 2008, 2006a, 2006b; Mota *et al.*, 2005, 2004a, 2004b), and tracking of both the ground surface and the approaching vehicle (Zhu *et al.*, 2006; Baehring *et al.*, 2005).

General Motors recently demonstrated a fleet of cars that can detect the position and movement of other vehicles up to a quarter of a mile away using vehicle-to-vehicle (V2V) communication (General Motors, 2007). Once the information of neighboring vehicles is inputted to the recognition system via V2V, it can determine whether there is a vehicle in the BSD zone or not.

It is noteworthy that active sensor-based and passive sensor-based systems require sensors and processing units only for BSD, and sensor fusion-based systems require multiple sensors and processing units (Amditis *et al.*, 2008; Rüder *et al.*, 2002). In particular, vision-based often requires hardware-accelerated implementation, such as field programmable gate arrays (FPGA), to meet the computing power requirement for real-time operation (Díaz *et al.*, 2006b; Mota *et al.*, 2004b). Because V2V-based systems can be used only when the vehicle and all neighboring vehicles are equipped with V2V including high-precision global positioning systems (GPS), it seems difficult to predict that the technology will be practically applied in the near future.

2.2. Rear Collision Warning

Nearly half of all accidents are rear-end collisions, and over 90% of injuries sustained by occupants whose vehicles are struck in rear-end collisions are to the neck region. More than 200,000 people in the U.S. suffer such injuries annually (Nissan, 2008a, 2008b). The mechanism of whiplash injuries closely involves the occupants bending their necks backward and tilting the head rearward and the driver's lack of awareness of the impending rear-end collision. Therefore, if the driver is informed of an impending rear-end collision, he/she can prepare for the collision and thereby reduce the severity of the impact. Sensors detecting the rear-end collision include mm-wave radar (MAZDA, 2007) and rearward camera (Akita *et al.*, 2006).

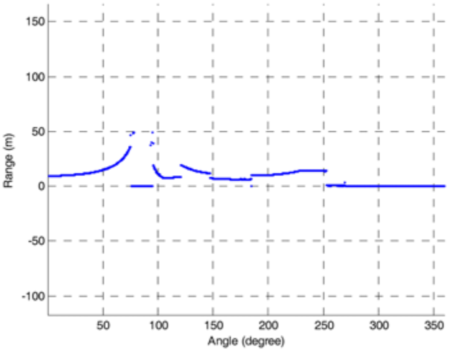
Furthermore, RCWS can activate an active headrest, which moves the headrest forward and upward to support the occupant's head in a rear-end collision situation. Previously used active headrests have mechanical structures which move the headrest forward only after collision occurs and the occupant's back pushes his/her seat (Nissan, 2008a; Lim, 2007). Recently, LEXUS released a rear pre-crash safety system, which can detect rear-end collision with mm-wave radar and actively activate the headrest (LEXUS, 2008). The so called pre-crash intelligent front headrest is able to move the headrest to a position supporting the occupant's head without the force generated when the occupant is pushed to his/her seat (Akaike and Nishimura, 2006).

2.3. Target Position Designation for Perpendicular Parking

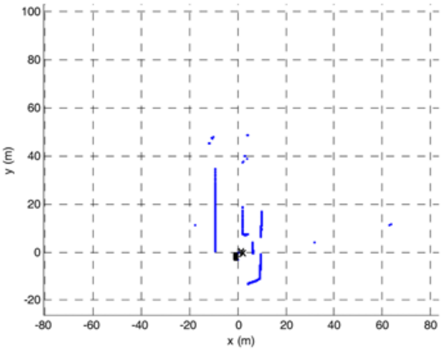
Our previous works on perpendicular parking provide a survey of target parking position designation methods (Jung *et al.*, 2008a). Target parking position designation methods can be divided into three categories: GUI-based (Jung *et al.*, 2006a), parking slot markings-based (Jung *et al.*, 2006b, 2006c, 2008b), and free space-based (Suhr *et al.*, 2008; Jung *et al.*, 2006d, 2007b). The method proposed by this paper belongs to the free space-based category, for which various methods, such as motion stereo-based (Suhr *et al.*, 2008), binocular stereo-based (Jung *et al.*, 2006d), and light stripe projection (LSP)-based (Jung *et al.*, 2007b), have been tried. Our previous work indicated that scanning laser radar could robustly and accurately establish the target parking position for perpendicular parking situations (Jung *et al.*, 2008a). As the stereo vision-based method requires enormous computation, it requires the development of special hardware. Furthermore, a number of unsolved challenges remain, such as the impact of harsh illumination, various vehicle colours, and reflective surfaces. Although the LSP-based method could be an economic solution for dark underground parking spaces, it cannot be used outdoors during daylight (Jung *et al.*, 2007b). The scanning laser radar has also had some weaknesses in the past such as being too expensive for a single purpose and too large for compact installation (Jung *et al.*, 2008a).

2.4. Target Position Designation for Parallel Parking

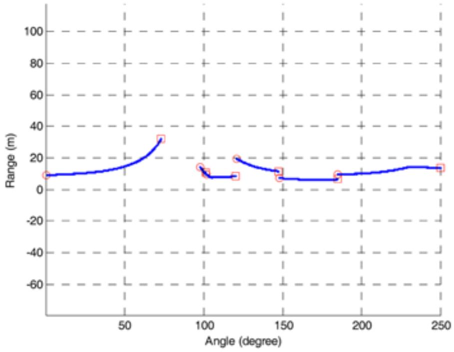
Contrary to the case of perpendicular parking, for which



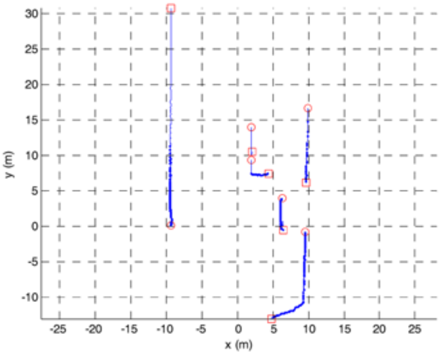
(a) Initial range data with respect to angle



(b) Initial range data in Cartesian coordinates



(c) Resultant clusters with respect to angle



(d) Resultant clusters in Cartesian coordinates

Figure 2. Preprocessing of acquired range data.

various sensors and signal processing technologies are tested with each limit and possibility, the ultrasonic sensor seems to be dominant. To precisely measure the edges of the free parking space, Hella developed a new sensor with a modified sensing area that is horizontally narrow and vertically wide (Heilenkötter *et al.*, 2007). Linköping University and Toyota both utilized the correlation between multiple range data sets, using multi-lateration (Pohl *et al.*, 2006; Degerman *et al.*, 2006) and rotational correction (Satonaka *et al.*, 2006), respectively.

3. METHOD MONITORING SIDE-REAR AREA DURING RUNNING

3.1. Preprocessing

Range data acquired by scanning laser radar are processed and converted into meaningful clusters. The preprocessing procedure consists of three steps: removal of invalid and isolated data, occlusion detection, and fragmentary cluster removal (Jung *et al.*, 2008a).

Occlusion is defined as an incontinuous position between consecutive two range data and can be recognized by finding a transition between invalid data and valid data. Two continuous valid data with longer distance than a threshold, e.g. 0.5m, also make an occlusion.

Figure 2(a) shows initial range data with respect to angle and Figure 2(b) shows initial range data in the Cartesian coordinate system. It can be observed that there are many invalid and noisy data. Figure 2(c) and (d) show range data clusters resulting from the preprocessing procedure. It can be observed that noisy data are removed and connected range data are recognized as a cluster. Although the range data of one scan period contains the location information of objects in two-dimensional (2D) space, it is acquired and processed as a one-dimensional (1D) array because it is represented with respect to consecutive angle values. Furthermore, as range values are listed in the order of consecutive angle values, a mutual relation between them is explicit unlike range data scattered over a 2D space. Therefore, an algorithm utilizing this characteristic can be simpler than one generally used for 2D object recognition and requires smaller computational power and memory.

For the sake of BSD and RCWS, recognized clusters are tracked by general Kalman filtering. The center point of the tracked cluster is used as the representative of the cluster.

3.2. BSD (Blind Spot Detection)

The proposed ISRSS detects potentially dangerous vehicles in the blind spot zone by finding range data clusters and tracking. In general, the BSD system monitors one of two vehicle sides, one being the driver’s seat side. The blind spot zone is defined as shown in Figure 3 such that it covers 45° with respect to the vehicle side surface and ranges 12 m in length and 5 m in width.

When driving at higher speeds than the threshold (e.g., 40 km/h), if the driver turns on the lane change indicator and a vehicle is in the blind spot zone, the system will inform the driver of this dangerous situation by audible and visual warning messages.

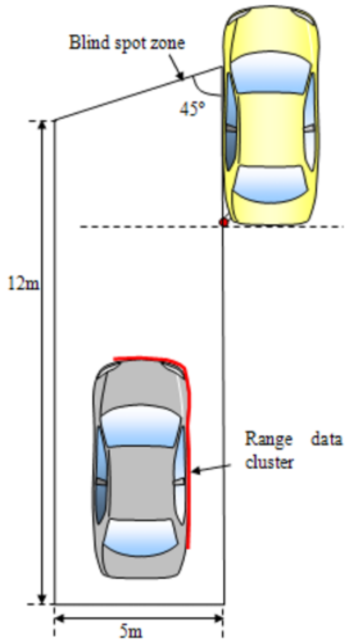


Figure 3. BSD monitoring zone.

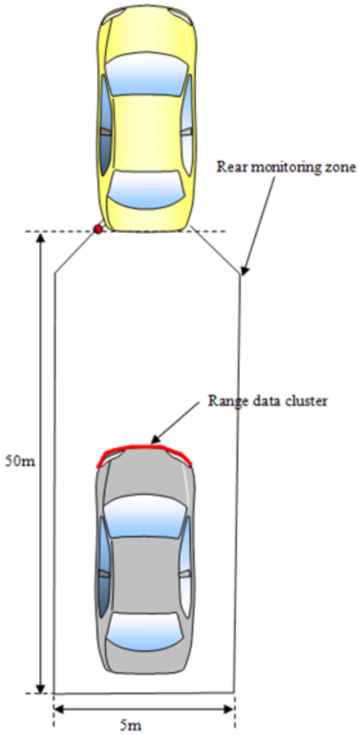


Figure 4. Rearward monitoring zone for RCWS.

3.3. RCWS (Rear Collision Warning System)

With the same operating principle, the proposed ISRSS detects a vehicle approaching dangerously from the rear as shown in Figure 4.

Displacement between consecutive detections can roughly estimate the speed of an approaching vehicle. Based on the estimate of TTC (time to contact), the ISRSS warns the driver to prepare for a potential rear-side collision. Equation (1) defines approximated TTC, t_c. Here, $d[n]$ means the measured distance to the object at nth sampling time, and v means the relative speed between the subjective vehicle and an object. t_s denotes the time difference between samplings.

$$t_c = \frac{d[n]}{|v|} = m\frac{d[n] \cdot t_s}{|d[n] - d[n-1]|} \tag{1}$$

4. TARGET POSITION DESIGNATION FOR PARKING ASSIST SYSTEM

An ISRSS can detect free space from the range data and designate the target parking position for automatic parking. In particular, because the proposed method uses only a single range data set corresponding to one scanning period, it can eliminate complicated calibration and error caused by odometry.

4.1. Perpendicular Parking Situation

Target position designation for perpendicular parking situations consists of six steps: rectangular corner detection of range data, round corner detection of range data, application of region of interest (ROI), application of free space constraints, recognition of main reference corner, and establishment of target position. In our previous work (Jung *et al.*, 2008a), it was shown that such steps could successfully designate the target position for perpendicular parking situations.

It is assumed that the range data from the scanning laser radar are acquired in a parking lot. Because a major recognition target, such as a vehicle or a pillar, appears as an “L”-shaped cluster in the range data, corner detection can detect vehicles and pillars. Corner detection is done by rectangular corner detection followed by round corner detection: round corner detection re-investigates clusters that fail in rectangular corner detection. Rectangular corner detection models a cluster as a cross-point of two orthogonal lines and round corner detection models it as a cross-point between a line and an ellipse. (Jung *et al.*, 2008a) for detailed description of rectangular and round corner detection.

It is assumed that the range data are acquired from a location where the driver manually starts parking and the target parking position is within a ROI, which is established by the field of view (FOV) and maximum distance. In the experiments, the FOV is set to rearward 160°, and the maximum distance is set to 25 m. Corners out of the ROI are regarded as irrelevant to the parking operation and are thus ignored. By selecting the nearest, called the main reference corner, to the subject vehicle, information pertaining to one side of the free space can be acquired. By investigating whether there is free space in the lateral direction of the main reference corner and selecting the

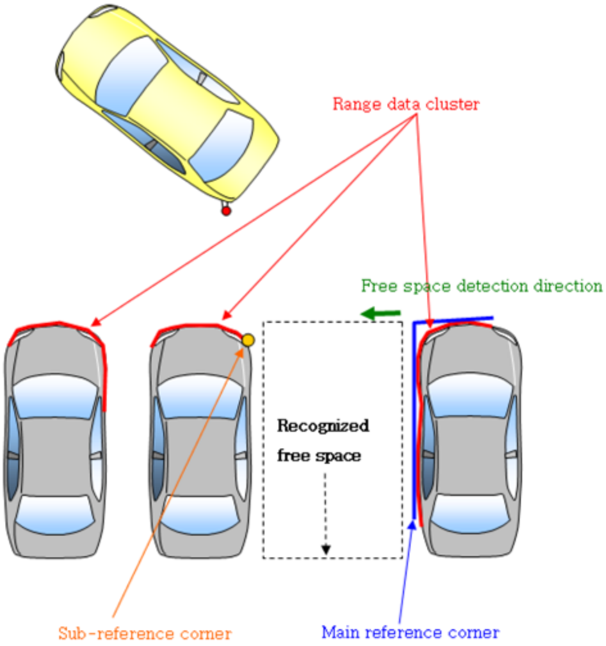


Figure 5. Free space detection for perpendicular parking situation.

nearest range data cluster in that direction, information pertaining to the other side of the free space can be acquired. The selected corner is called the sub-reference corner. Consequently, with the main reference corner and sub-reference corner, the free parking space is recognized, and the target position is established by considering the subject vehicle's size, e.g., width=1.6 m and length=3.5 m. Figure 5 shows the main reference corner, investigation of free space constraints, sub-reference corner, and recognized free space.

4.2. Parallel Parking Situation

In our previous works (Jung *et al.*, 2007a, 2008a), we suggested that the method used for perpendicular parking situations could be applied to parallel parking situations with only a few slight adjustments. Actually, if the farther parked vehicle appeared as an 'L'-shaped cluster in the range data as shown in Figure 6(a), the same method could be used only by changing the target position's direction orthogonal to that of the parallel parking case (Jung *et al.*, 2007a). However, it was found that if the vehicle passed the free space, the farther parked vehicle did not have an 'L'-shape any longer, as shown in Figure 6(b). Therefore, the main reference corner detection gave a large error because of the failure of corner detection and incorrectly established direction of the free space investigation interfered with sub-reference corner detection. Furthermore, in the case of parallel parking, because the free space was longer in longitudinal direction and wider in lateral direction than the perpendicular case, there was greater possibility for free space investigation and sub-reference corner detection to fail.

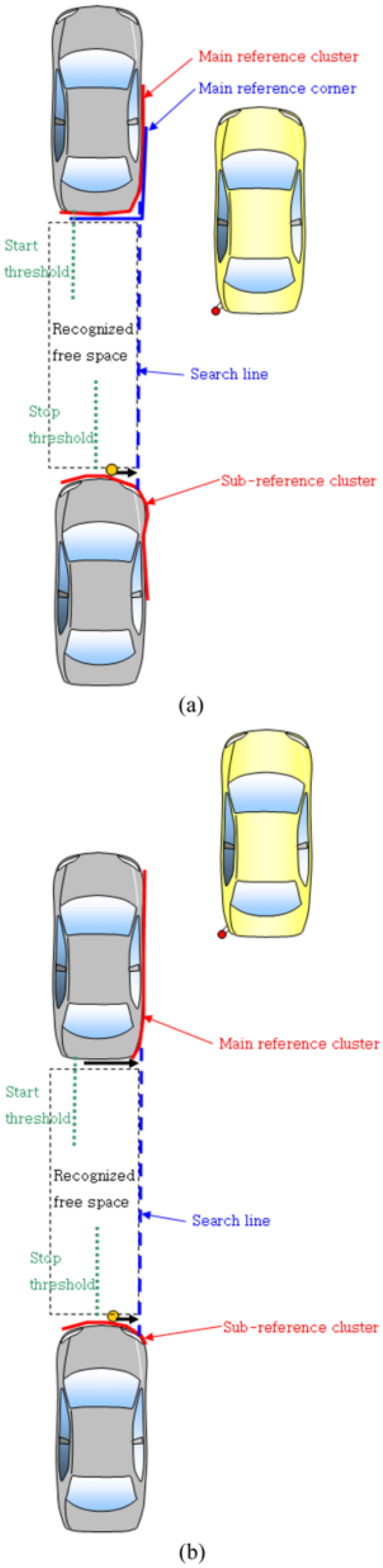


Figure 6. Free space detection for parallel parking situation.

The newly developed method proposed in this paper is

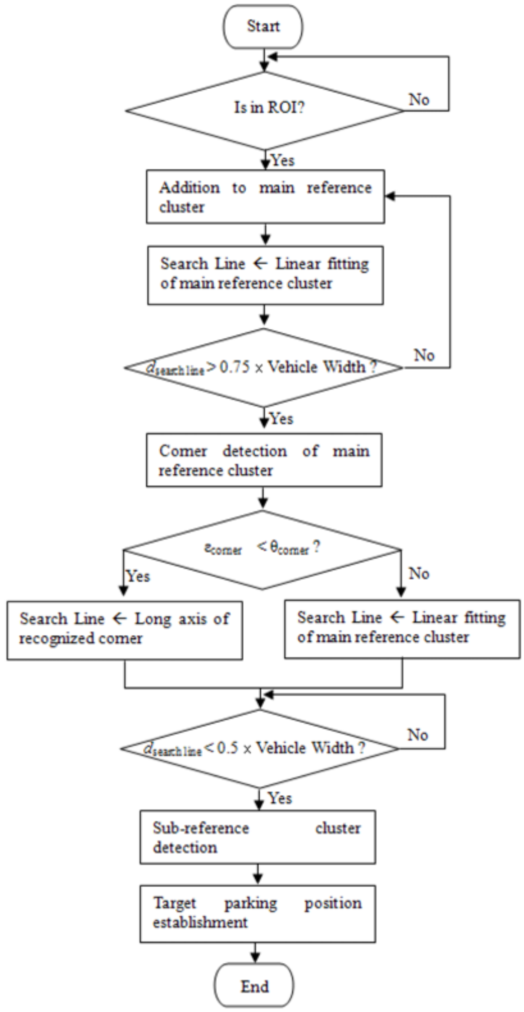


Figure 7. Flowchart of target parking position established for parallel parking situations.

similar to the method using ultrasonic sensors and odometry because it starts from the adjacent parked vehicle. The algorithm is depicted in Figure 7 and consists of four main steps: main reference cluster detection, search line establishment, sub-reference cluster detection, and target position designation. It is noteworthy that the main reference cluster and sub-reference cluster are different from the main reference corner and sub-reference corner of the previous section.

It is assumed that range data points are investigated counterclockwise from a line connecting the scanning laser radar and the same side's front corner. Main reference cluster means valid range data points from when the range data point enters into the ROI to when it diverges from the previous points. The ROI used is the area between the 'vehicle length' and 5 × 'vehicle length' in the longitudinal direction and between 0 to 3 × 'vehicle width' in a lateral direction. When adding a range data point to the main reference cluster, the search line is updated by the linear fitting of the main reference cluster. If the distance between the new range data point and the search line becomes longer than a threshold, e.g. 75% of 'vehicle width', the new point is supposed to diverge from the previous points. Once the main reference cluster is recognized, corner detection is applied, and whether the cluster is 'L'-shaped or not is determined by comparing corner detection error, θ_{corner}, with a certain threshold, θ_{corner}. If the main reference cluster is recognized as a corner as seen in Figure 6(a), the search line is set to the long axis of the corner. Contrarily, if the main reference cluster is recognized as a line as shown in Figure 6(b), the search line is set to the line.

Sub-reference clusters provide information pertaining to the farther parked vehicle location. If the distance between range data point and search line, $d_{\text{search line}}$, falls below 50% of the 'vehicle width', a range data cluster connected to the range data point is recognized as a sub-reference cluster. In this manner, range data points between the main reference and sub-reference cluster are ignored. To reduce the effect of noise by applying hysteresis, the threshold of the main reference endpoint, 75%, and the threshold of the sub-reference cluster start-point, 50%, are set differently.

Once clusters on both sides are recognized, the space between the main reference endpoint and the sub-reference nearest point is recognized as free space. The sub-reference nearest point is acquired by projecting a point of sub-reference cluster, which is closest to the search line, onto the search line. By setting the middle of the target position's sideline to the mean of these two border points and aligning the sideline with the search line, the target parking position is established.

5. EXPERIMENTAL RESULTS

5.1. Experimental Setup

The authors installed a scanning laser radar (SICK LD-OEM) on the left side of the rear of the experimental vehicle, as shown in Figure 8. A brief specification of this sensor is as follows: the field of view is 360°, the angular resolution is 0.125°, the range resolution is 3.9 mm, the

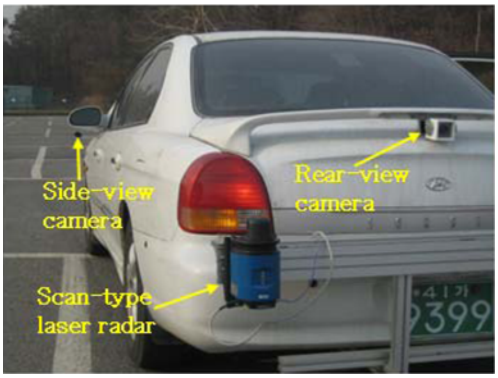


Figure 8. Test vehicle with scanning laser radar and side/rear cameras for monitoring.

maximum range is 250 m, the data interface is a controller area network (CAN), and the laser class is 1 (eye-safe). The authors installed two cameras for rearview and side-view, respectively, as shown in Figure 8 to record the experimental situation. These cameras were used only for analysis. A rear-view camera was used for recording perpendicular parking situations and RCWS. To cover a wide range of rearward situations, a fisheye lens with 120° FOV was used. A side-view camera was used for recording parallel parking situations and BSD situations.

5.2. Experimental Results of BSD

To allow other vehicles to overtake our test vehicle, the test vehicle traveled at relatively slow speeds, e.g., 80 km/h. Range data and synchronously acquired images were stored for analysis.

Figure 9 shows the location of a vehicle approaching the test vehicle and passing and in the BSD warning state. This sequence consists of 25 samplings. Locations designated by dot marking are in a normal state, and locations designed by 'x' marking are in a warning state. The arrow denotes the moving direction of the vehicle. It can be observed that when the vehicle is inside of the BSD zone, it is recognized as a dangerous vehicle.

For the purpose of performance evaluation, range data and sideward images were recorded while driving on a highway both during the day and at night. In total, 13025 frames, i.e., a set of range data and images, were recorded. Among them, 2381 frames contained vehicles in the BSD zone. The proposed method showed perfect performance: 100% recognition rate without false positive and false negative. Figure 10 shows examples of vehicle detection in the BSD zone. The left image of each case shows captured range data and detection results. At the origin, the black round rectangle represents the test vehicle and a small area marked by red lines near the test vehicle represents the BSD zone. A blue rectangle around the range data in the BSD zone signifies the range cluster causing a BSD warning. The right image of each case shows the captured image with a sideward camera. As the proposed method uses only range data from the scanning laser radar, the performance does not depend on the illumination conditions and appearance of the other vehicles.

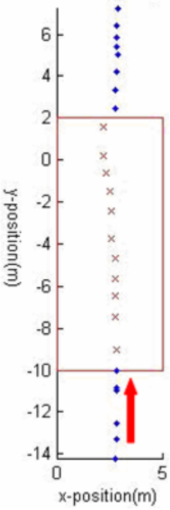


Figure 9. Vehicle locations and BSD warning state.

(a) Truck

(b) Light-weight vehicle

Figure 10. Recognized adjacent vehicle in BSD zone.

5.3. Experimental Results of RCWS

To make the following vehicle approach the test vehicle, the test vehicle traveled relatively slowly, e.g., 80 km/h. However, in a casual driving situation on a public roadway,

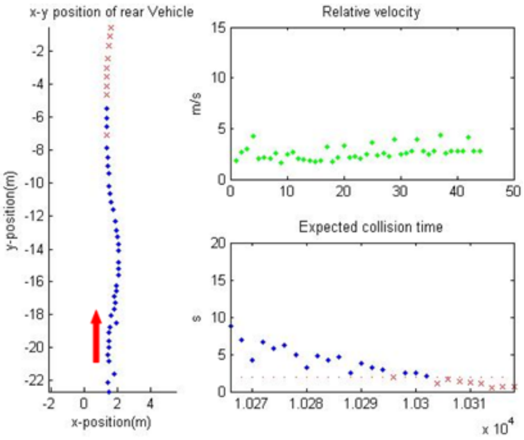
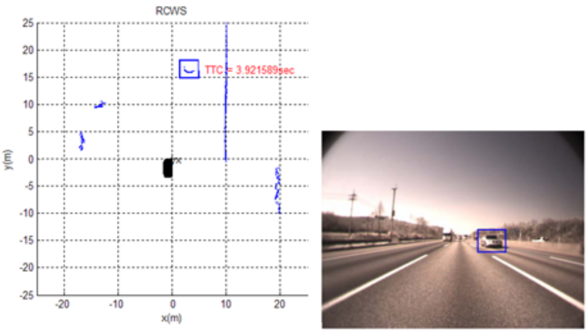
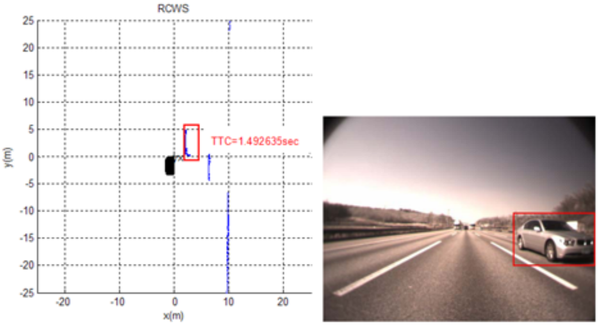


Figure 11. Vehicle locations, relative speed, TTC, and RCWS warning state.



(a) Normal condition: TTC=3.921589 sec



(b) Warning condition: TTC=1.492635 sec

Figure 12. Recognized vehicle in normal and warning condition.

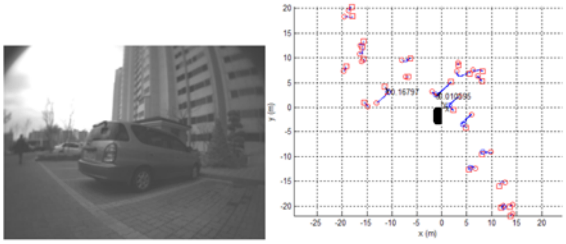
we could not experience a rear collision situation. Instead, by regarding the vehicle in the left lane as a following vehicle, the RCWS system was validated.

Figure 11 shows the locations of an approaching vehicle and RCWS warning states. This sequence consists of 44 samplings. In the left picture, locations designated by dot markings are in a normal state, and locations designated by ‘x’ markings are in a warning state. The arrow denotes the moving direction of the vehicle. It can be observed that when the TTC went below a threshold, e.g., 2 sec, it was recognized as a dangerous vehicle, as shown in the image below on the right.

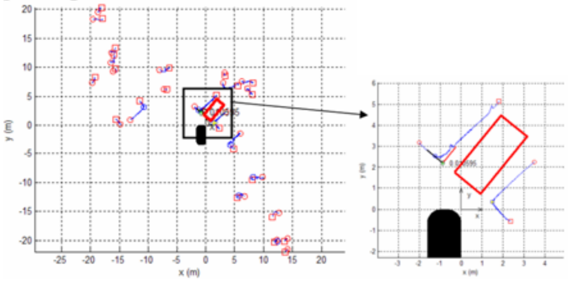
For performance evaluation, range data and rearward images were recorded while driving on a highway both during the day and at night. In total, 2319 frames were recorded, and 110 frames among them met RCWS operation conditions. The proposed method demonstrated perfect performance: a 100% recognition rate with no false positives or false negatives. Figure 12 shows examples of RCWS operation; Figure 12(a) shows normal conditions where the TTC of the approaching vehicle is larger than a threshold, and Figure 12(b) shows warning conditions where the TTC is less than the threshold.

5.4. Experimental Results of Perpendicular Parking

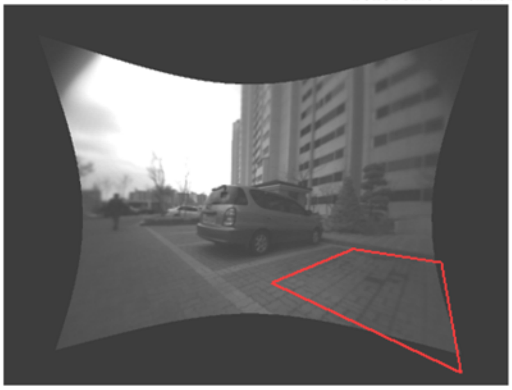
We tested our system in 112 situations and confirmed that it is able to designate the target parking position at the desired location in 110 situations. This data set was acquired when the driver started the parking procedure. Therefore, the recognition rate was 98.2%. The average processing time on a PC with a 1-GHz operation frequency is 615.3 msec. It is noteworthy that the parking application uses only one range data set unlike RCWS, and that scanning laser radar-based systems work well in spite of situations that are difficult for vision-based types, such as daytime/night-time, outdoors/indoors, and against the sun. (Jung *et al.*, 2008a) for detailed experimental result of perpendicular parking situations.



(a) Image showing the test situation of perpendicular parking (b) Recognized corners



(c) Recognized target position (d) Recognized reference vehicles



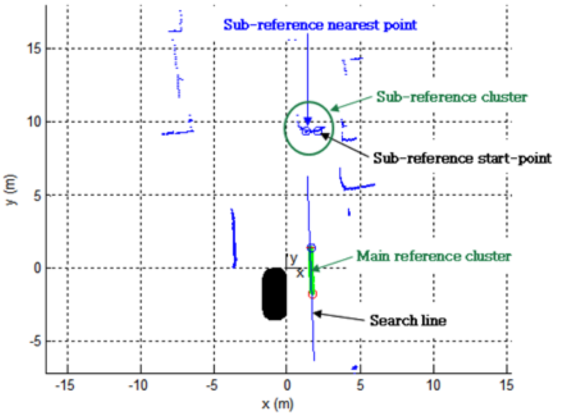
(e) Target position projected onto undistorted input image

Figure 13. Target parking position designation for perpendicular parking situation.

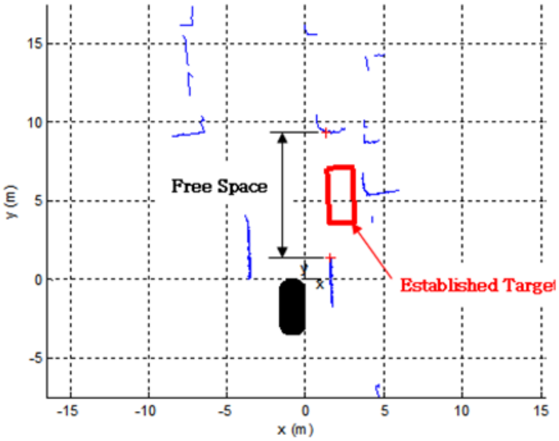
Figure 13(a) shows the test situation of perpendicular parking. In this case, the target position was located at an apartment parking slot and between two parked vehicles. Figure 13(b) shows recognized corners. Figure 13(c) shows recognized target parking position, and Figure 13(d) shows recognition results in more detail. The corner recognized as the main reference vehicle is marked by an ‘L’ with the fitting error and sub reference vehicle marked by a small ball that is a corner recognized in the initial corner detection. The distance between two reference vehicles was measured as 3.23 m and was larger than the test vehicle width. Figure 13(e) shows target parking position projected onto an undistorted input image. As explained in the experimental settings, we used a fisheye lens to cover wider FOV in perpendicular parking situations. The acquired input images were converted into undistorted images based on a radial distortion model. A Caltech calibration toolbox (Bouguet, 2009) and an extrapolation-based refinement method (Jung *et al.*, 2006e) were used for lens calibration and image rectification. It can be observed that the established target position is correct and proper.

5.5. Experimental Results of Parallel Parking

Figure 14 shows the procedure for how the proposed method establishes a target position. Figure 14(a) shows the main reference cluster recognized, the search line by its linear fitting, and sub-reference cluster recognized. Two 'o' markings on the sub-reference cluster depicts the sub-reference start-point, where the distance between the range data point and search line becomes below a threshold, and the sub-reference nearest point, which is the closest to the search line among the sub-reference cluster points. Figure 14(b) shows the recognized free space between the main reference cluster endpoint and the sub-reference cluster nearest point and established target parking position.



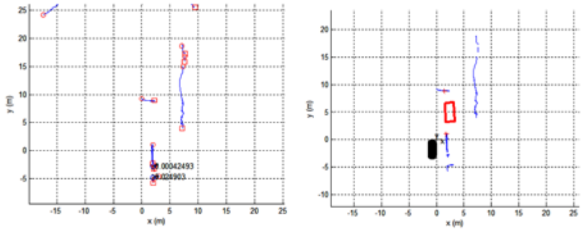
(a) Recognized main reference and sub-reference cluster



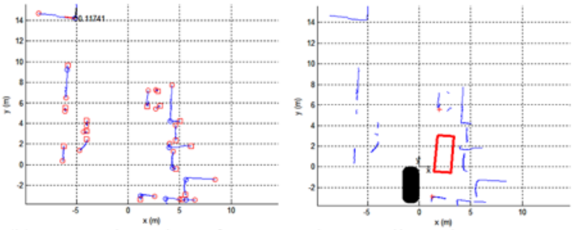
(b) Recognized free space and established target position

Figure 14. Target position designation procedure for parallel parking position.

Figure 15 shows that the proposed method can successfully designate target position even when the previous method of (Jung *et al.*, 2008a) fails. Figure 15(a) shows a case when the range data of the farther parked vehicle's sideline is not acquired, and the cluster is not 'L'-shaped. The previous method fails as shown in the left figure because corner

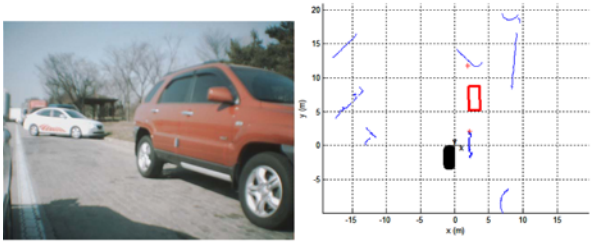


(a) Farther parked vehicle is not 'L'-shaped

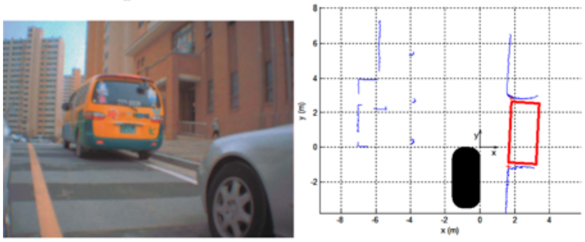


(b) Range data along free space is complicated

Figure 15. Cases when the proposed method solved the failure of the previous method.



(a) Farther parked vehicle is slanted



(b) Free space is very narrow

Figure 16. Cases when the proposed method is superior to the previous in performance.

detection is based on the 'L'-shape assumption. In contrast, because the proposed method does not use such an assumption, it can successfully designate a target parking position as shown in the right figure. Figure 15(b) presents a case when the range data along the free space is complicated, and the previous method fails in the investigation of free space constraints. In contrast, because the proposed method ignores range data points between the main reference end-point and the sub-reference start-point, it can simply recognize free space and successfully designate a target parking position as shown in the figure on the right. Considering that the main reference cluster of Figure 15(a) is a line and that of Figure 15(b) is a corner, the proposed method operates well in both modes.

Figure 16 shows cases when the proposed method is superior to the previous one of (Jung *et al.*, 2008a) in regards to performance. Figure 16(a) is the case when the farther parked vehicle is slanted. Because the previous method uses the vehicle as a main reference corner, it wrongly designates the target parking position. The ultrasonic sensor-based method also fails to find the free space border because of the slanted range data of the vehicle. Figure 16(b) is the case when the free space is very narrow. Although the previous method can successfully designate the target parking position, the ultrasonic sensor-based method fails to operate accurately because of the lack of range data near the vehicles' front and rear edges (Pohl *et al.*, 2006; Satonaka *et al.*, 2006).

We tested our system in 52 situations and confirmed that it was able to designate a target parking position at the desired location in 48 situations. This data set was acquired when the driver started the parking procedure. Therefore, the recognition rate is 92.3%. To investigate the accuracy of the recognized free space, we measured free space width 25 times at the same location. Figure 17 shows the measured free space; the average is 9.6959 m, and the standard deviation is 0.0384 m. The worst case is different from the average by just 10 cm, which is definitely smaller than that of the ultrasonic sensor-based approaches (Heilenkötter *et al.*, 2007; Pohl *et al.*, 2006; Degerman *et al.*, 2006; Satonaka *et al.*, 2006).

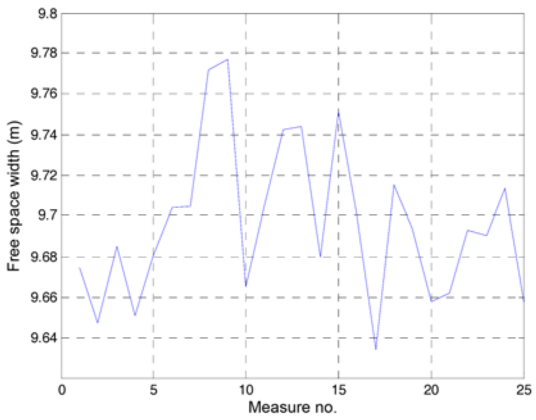
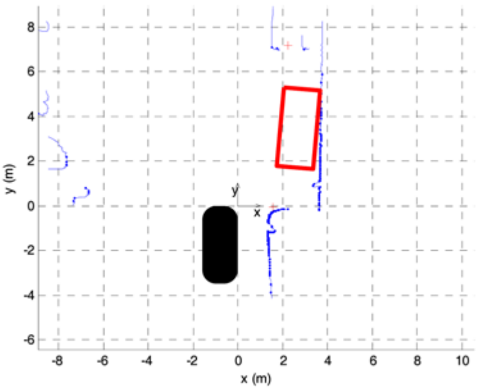
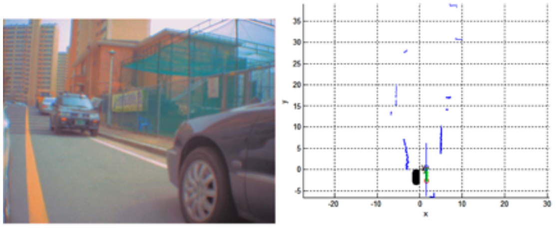


Figure 17. Measured free space width at a fixed position.



(a) Main reference cluster shows ambiguity between a line and a corner



(b) Ground surface is not plane

Figure 18. Cases when the proposed method failed.

Figure 18 shows those cases in which our proposed method failed. Figure 18(a) provides the case when the ray of the scanning laser radar is aligned with the back end surface of a parked vehicle. In this case, as the range data of the back end surface is lost, the range data cluster shows ambiguity between a line and a corner. Even if corner detection is applied, the long axis contains too much error. Similarly, linear fitting also generates an erroneous search line. It is noteworthy that if the range data of the back end surface is missed wholly, linear fitting becomes accurate, and there is no longer any error. Figure 18(b) shows cases when the ground surface is not plane and when the range data of a farther parked vehicle is not acquired.

6. CONCLUSION

This paper proposed a novel integrated surrounding environment recognition system using a single scanning laser radar. The proposed system integrates and implements four system functions: BSD (blind spot detection), RCWS (rear collision warning system), semi-automatic perpendicular parking, and semi-automatic parallel parking. While the vehicle is running, range data from the scanning laser radar is filtered and clustered. By monitoring range data clusters in the sideward area, potentially dangerous vehicles can be reported to the driver. Similarly, by monitoring range data clusters in the rearward area and estimating their speed, rapidly approaching vehicles can be recognized. After corners are recognized by rectangular and round corner detectors, relation to the subjective vehicle and free space constraints successfully detect available free parking spaces for perpendicular parking situations. By detecting the nearest range data cluster and estimating its line equation, the proposed method separates the main reference cluster and the sub-reference cluster and then recognizes free parking spaces for parallel parking situations.

Our proposed ISRSS is assumed to reduce the total system price because it uses only one sensor and an integrated processing unit. Furthermore, as the scanning laser radar can provide very precise angular resolution compared with competing sensors such as mm-wave radar, stereo vision, and motion stereo vision, the processing algorithm for the scanning laser radar is assumed to be more reliable and simpler.

The proposed method is proven in real road situations. BSD and RCWS were demonstrated with 13025 and 2319 frames, respectively. Although a 100% success rate with a limited number of test data could seem rash, the feasibility of our proposed method seems to be explicit considering the fact that the operating range of the sensor is 250 m. Target position designation for a perpendicular situation was evaluated with 112 situations, and the success rate was 98.2%. Similarly, target position designation for a parallel parking situation was evaluated with 52 situations, and the success rate was 92.3%.

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