Ground Reflection Elimination Algorithms for Enhanced Distance Measurement to the Curbs Using Ultrasonic Sensors

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BIOGRAPHIES

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ABSTRACT

In autonomous driving vehicles, recognizing objects in the environment, such as other vehicles, pedestrians, crossroads, lanes, and curbs, is necessary. Curbs separate roads from sidewalks, and if they are properly detected and recognized, autonomous vehicles would be prevented from accidentally encroaching onto sidewalks. Various distance-measuring sensors such as radars, lidars, stereovision sensors, and ultrasonic sensors can be used to obtain a vehicle's distance from the curb. However, a cost-effective curb-detection and recognition system that is robust under various weather and light conditions is desirable for most vehicles. Automotive ultrasonic sensors are good candidates for this application owing to their low cost, and as they are already widely used in most vehicles—especially for parking assistance. Although ultrasonic sensors are useful for measuring distances to curbs, their observed performance during our field tests was poor, with frequent outliers and unreliable distance outputs. We thus attempted to overcome these limitations by using multiple ultrasonic sensors simultaneously. We tested an averaging algorithm and a majority-voting algorithm as distance-estimation algorithms using measurements from three ultrasonic sensors mounted on a vehicle. The distance-estimation performance obtained was improved but still insufficient for reliable curb detection. We found that the measurements were sometimes being made from the ground instead of the curb, which significantly degraded the distance-estimation performance. The ultrasonic wave transmitted from the sensor can be reflected from any object within the beam width of the antenna attached to the sensor, even when the antenna is properly oriented toward the curb. We therefore present ground-reflection elimination algorithms for ultrasonic sensors for enhanced distance-estimation performance and verify their effectiveness through field tests. Three ultrasonic sensors were installed on the lower side of a vehicle for the experiment. We compared the distance-estimation performance with and without the ground-reflection elimination and demonstrated significant performance enhancement with the proposed algorithms.

INTRODUCTION

The technologies used for autonomous driving vehicles include environment recognition, precise positioning, and decision making for unexpected situations. In particular, recognition of objects in the environment such as other vehicles, pedestrians, crossroads, lanes, and curbs is an important technology. Among these various surrounding environmental objects, curbs are important for driving situations. Curbs are stones that separate roads and sidewalks. In order to prevent autonomous vehicles from accidentally encroaching onto sidewalks, it is necessary to accurately detect and recognize curbs. A curb-detection technology is also applicable for implementing an automatic pull-over system that automatically pulls over a vehicle to the curb in an emergency situation such as the heart attack of a driver.

Various distance-measuring sensors such as radars, light detection and rangings (lidars), stereovision sensors, and ultrasonic sensors can be used to provide the vehicle's distance to the curb. The measured distance information can be used for curb detection and recognition. For the purpose of measuring the distance to the curb, the majority of studies in the extant literature comprise the use of 3D lidars and stereovision sensors because of their good performance under good weather and light conditions [1]–[7]. However, there are three disadvantages of using lidars: high price, existence of blind spots, and the dependency of its accuracy on the weather. In general, the price of a 3D lidar is too high for use in most vehicles. In addition, the existence of a blind spot is another weak point of lidars. Lidars are generally attached to the roof of the vehicle in order to obtain a 360° view of the surroundings. As the roof of the vehicle prevents the lidar from observing objects below it, lidar cannot be used to detect objects near the bottom of the vehicle. This can be a critical problem in the case of its use in curb-detection systems as the curb may be located very close to the vehicle. Lastly, their performance is degraded in harsh weather such as rain or snow [8]. Vision sensors also encounter a problem in curb-detection applications. The performance of vision sensors is largely impacted by light conditions. They are significantly influenced by shadows, brightness, weather, etc. Therefore, a sensor that is cost-effective and robust under various weather and light conditions is desired for curb-detection and recognition systems in most vehicles.

Automotive ultrasonic sensors are good candidates for the aforementioned application owing to their low cost and as they are already widely used in most vehicles—especially for parking assistance [9],[10]. Although the ultrasonic sensors are useful for measuring vehicle distances to curbs, their observed performance is poor with frequent outliers and unreliable distance outputs. This is because the accuracy and reliability of a single ultrasonic sensor is not high as compared with other sensors such as lidars. Considering the lower performance of ultrasonic sensors, it is understandable that they have not been considered effective for measuring the distance from a vehicle to a curb in the extant literature. We attempted to overcome these limitations by using multiple ultrasonic sensors simultaneously. We tested an averaging algorithm and a majority-voting algorithm as simple distance-estimation algorithms using the measurements from three ultrasonic sensors mounted on a vehicle. The obtained distance-estimation performance was improved but still insufficient for reliable curb detection.

After careful observations, we found that the measurements were made from the ground instead of the curb, which significantly degraded the distance-estimation performance. The ultrasonic wave transmitted from the sensor can be reflected from any object within the beam width of the transmitter attached to the sensor even when the sensor is properly oriented toward the curb. This phenomenon is called ground reflection or ground echo [11]–[13]. In this paper, we present a ground-reflection elimination algorithm for ultrasonic sensors in order to enhance the obtained distance-estimation performance and verify the effectiveness of the proposed algorithm through field tests. Three ultrasonic sensors were attached to the lower side of a vehicle for the experiment. The ground-reflection elimination algorithm is introduced in the following sections. In order to use the algorithm without a serious decrease in system availability, it is necessary to use multiple mutually complementary sensors. Therefore, an algorithm with multiple sensors is described in the last section, and the conclusions of this study are presented at the end of this paper.

CURB DETECTION USING A SINGLE ULTRASONIC SENSOR

An important feature of an ultrasonic sensor is that a single sensor can detect only one point of an object at a time. For instance, if the signal transmission rate of an ultrasonic sensor is 10 Hz, only 10 measurements can be obtained in a second. In order to detect an object with high accuracy and reliability, it is important to obtain a sufficient number of measurements. The structure of an ultrasonic sensor we used in our study is illustrated in Fig. 1. The specifications of this ultrasonic sensor are shown in Table I. In order to implement a cost-effective curb-detection system, this ultrasonic sensor was selected because a single sensor costs under USD 15. All the measurements presented in this paper are collected by installing this sensor on the side of a vehicle to obtain its distance to a curb.

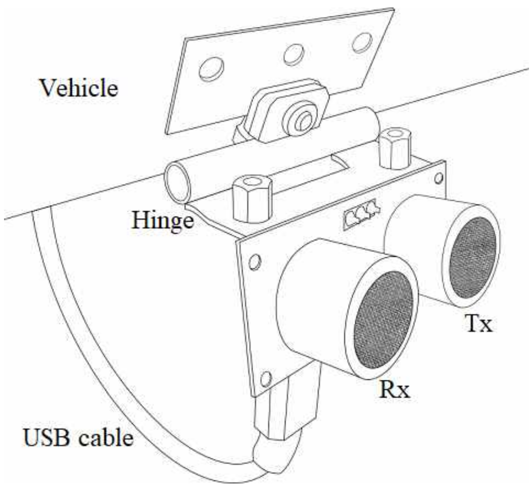

Figure 1. Structure of the ultrasonic sensor for curb detection.

Table 1. Specifications of the ultrasonic sensor used.

Frequency of ultrasonic sound	40 kHz
Frequency of measurement	10 Hz
Beam angle	15°
Minimum detection range	2 cm
Maximum detection range	10 m
Resolution	0.1 cm
Operation voltage	5 V

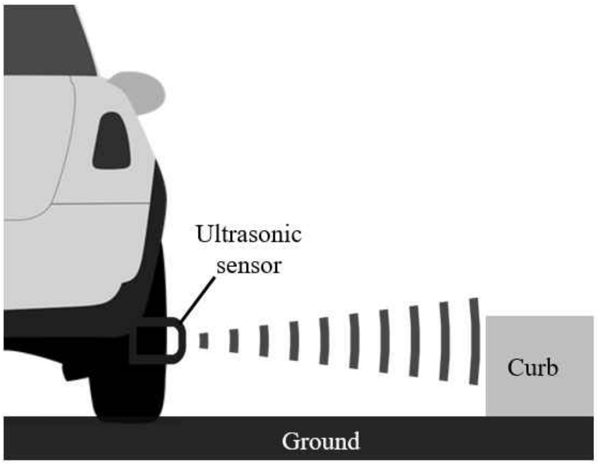

Figure 2. Ordinary curb-detection scenario.

Figure 2 shows a simplified scenario in which the sensor detects curbs. The sensor is directed toward the curb, and the ultrasonic beam angle of the sensors is approximately 15°. Figure 3(a) shows a sample measurement from the sensor that is detecting a curb in the static condition. The actual distance between the sensor and the curb is set as 1.6 m. The maximum error in the measurements is 0.01 m, and it can be stated that the sensor provides stable outputs with high accuracy.

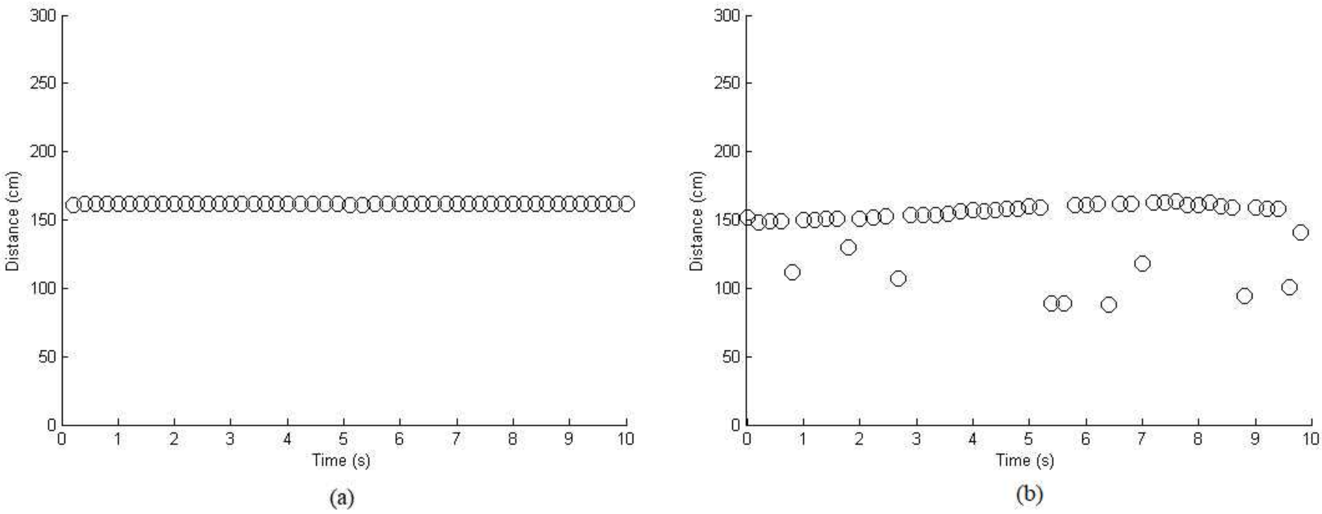

Figure 3. (a) Curb-detection measurements in static condition.
(b) Curb-detection measurements in dynamic condition.

However, the performance of the sensor is different in the dynamic condition. Figure 3(b) shows a sample measurement from the sensor that detects the curb under dynamic conditions, which means that the vehicle is moving. As the vehicle moves, the distance between the sensor and the curb changes. The actual distance between the sensor and curb is maintained 1.5 m at a constant speed. The maximum error in the measurements in Fig. 3(b) is 0.62 m, which is much greater than that in the static condition. This is because external influences are generated owing to the movement of the vehicle, such as wind flow, vibration, and the orientation of the vehicle. These influences change the orientation of the sensor slightly for every detection. Therefore, the sensor cannot collect data from a desired point on the curb in every detection. The sensor often measures the distance to other surrounding objects instead of the distance to the curb. Although there are various environmental objects on the roadside, the ground is the most commonly occurring object that the sensor detects other than curbs. The reflection from the ground instead of the curbs is referred to as the ground-reflection effect in this paper. The analysis of the ground-reflection effect is detailed in the next section.

ELIMINATION OF THE GROUND-REFLECTION EFFECT

As indicated in Fig. 2, the ultrasonic beam has a width of 15°. This means that an object can be detected when it is within the beam angle. This is a great difference between ultrasonic sensors and lidars. Lidars detect objects with a narrow laser beam. When the beam is narrow, the reflecting surface of the object can be assumed to be a point. However, when the beam is wide, such as in the case of ultrasonic sound, the reflection surface cannot be assumed to be a point. In this case, the transmitted ultrasonic signal is reflected from a number of points on various objects. However, from among these reflection surfaces, only one point is detected because an ultrasonic sensor cannot detect multiple reflection signals. The ultrasonic sensor only detects the earliest returned signal, which indicates the signal reflected from the object nearest to the sensor.

After conducting several experiments, we observed that the ground has a major influence on the result. Figure 4 shows a scenario wherein a sensor detects the ground instead of the curb. If the distance between the vehicle and the curb becomes greater than the initial condition where the beam direction was set to the curb, the ground reflection can occur. This impedes the detection of curbs and induces errors. In order to improve the performance of the curb-detection system, it is important to detect and eliminate the measurements in which ground reflection has occurred.

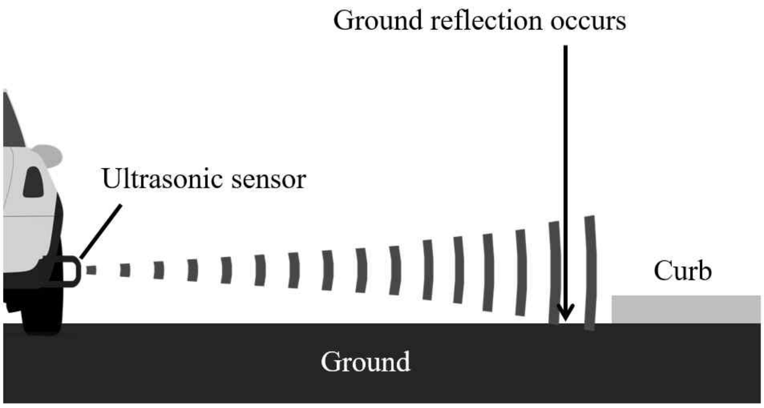

Figure 4. Scenario wherein a sensor detects the ground instead of the curb.

In order to detect and eliminate ground reflection, a threshold is required for determining whether the measurement is reflected from the ground or curb. The threshold can be derived based on the lane and vehicle widths. When a vehicle is driving in the closest lane from the curb, the expected distance to the curb $d_{curb}(1)$ can be expressed as shown below.

$$d_{curb}(1) = (W_{Lane} - W_{Vehicle}) / 2 \quad (1)$$

where W_{Lane} is the width of the lane, and $W_{Vehicle}$ is the width of the vehicle. When a vehicle is driving in the N^{th} lane from the outside, the expected distance to the curb $d_{curb}(N)$ can be expressed as shown below.

$$d_{curb}(N) = (N - 1)\, W_{Lane} + (W_{Lane} - W_{Vehicle}) / 2 \quad (2)$$

These equations are based on an assumption that the vehicle is driving in the center of the lane. Based on (2), we suggest a ground-reflection elimination algorithm that identifies and eliminates the measurements in which ground reflection has occurred. For example, $d_{curb}(N)$ is calculated as 1.2 m if W_{Lane} is 4.2 m, $W_{Vehicle}$ is 1.8 m, and the vehicle is driving in the closest lane from the curb. Thus, measurements smaller than 1.2 m are likely due to ground reflection. Because the lane and vehicle widths are fixed, this method is simple to apply; however, it is necessary to determine which lane the vehicle is driving in. There are existing lane detection technologies based on vision sensors [14]–[18] or Global Navigation Satellite Systems (GNSSs) [19]–[22]. However, the vision sensors are influenced by weather and light conditions [23],[24], and the GNSS sensors are vulnerable to radio frequency interference [25]–[32] and ionospheric effects [33]–[37]. Therefore, it is desired that the ultrasonic-sensor-based curb-detection system can determine the driving lane information by itself without relying on additional sensors. This is possible if multiple ultrasonic sensors are utilized, which is discussed in the next section.

After the ground-reflection measurements are eliminated, the remaining data represents the measurements of the distance between the vehicle and curb. However, after the elimination, the availability of the curb-detection system can decrease considerably because the eliminated measurements are not replaced or interpolated. The decreased availability of the system can become a critical problem for ensuring safety. Therefore, a solution that can prevent this decrease in availability is required. In order to solve this problem, we implemented a hardware platform with multiple ultrasonic sensors. The preliminary experiments for collecting the curb-detection data with multiple ultrasonic sensors were performed in our previous work [38]. The methods and advantages of using multiple sensors will be detailed in the next section.

GROUND-REFLECTION ELIMINATION ALGROITHM WITH MULTIPLE ULTRASONIC SENSORS

In order to prevent a considerable decrease in the availability of the system while eliminating the measurements wherein ground reflection occurred, we suggest the use of multiple sensors instead of a single sensor. The clear advantage of using multiple sensors is that the number of measurements obtained simultaneously is increased. In the case of the use of a single sensor, only one measurement is collected in one epoch. However, in the case of the use of multiple sensors, i.e., N sensors, N measurements are collected simultaneously in a single epoch. The measurements that are simultaneously collected are useful because they can be used to crosscheck or mutually complement each other. A decrease in the availability was the main problem with the use of a single ultrasonic sensor. When using a single sensor, there are no additional measurements that can replace or complement the eliminated measurement after performing the ground-reflection elimination. However, with multiple sensors, the system availability can be improved when a measurement is eliminated because the other sensors can detect the curb at the same time. The system can be unavailable when all the sensors detect the ground simultaneously, but this does not occur frequently. Therefore, the overall availability of the system can be improved when multiple sensors are used.

When three or more ultrasonic sensors are used, a majority-voting algorithm can be adopted to aid in determining the measurements in which ground reflection occurred. There is a probability of making an incorrect decision if the identification of the measurements in which ground reflection occurred is based only on a threshold value. This probability becomes higher when the actual distance between the vehicle and curb is slightly greater than the threshold value. In such scenarios, the use of

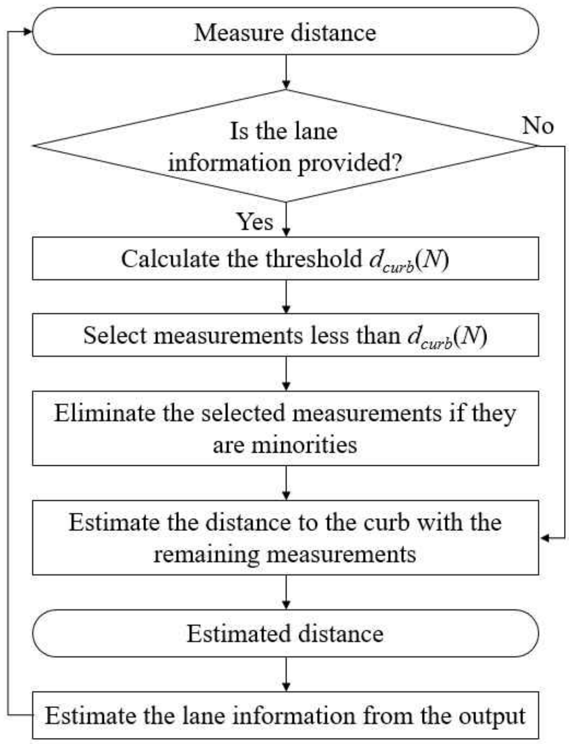

Figure 5. Flowchart of the ground-reflection elimination algorithm.

a secondary algorithm (i.e., majority-voting algorithm) that double-checks that ground reflection occurs would be useful. Therefore, the use of the majority-voting algorithm for determining the occurrence of ground reflection can provide a system performance that is superior to that obtained when using only the threshold. The majority-voting algorithm is used after filtering the measurements using a threshold value. In some cases, an incorrect decision may be made if a measurement in which ground reflection occurs is not eliminated because it is slightly greater than the threshold value. Nonetheless, the majority of the measurements obtained simultaneously can be used to detect the curb regardless of the occurrence of such an incorrect decision. Therefore, on using the majority-voting algorithm after making the incorrect decision, it is found that the minority of the measurements are outliers, which indicates that they are results obtained due to ground reflection.

The algorithm used to eliminate the measurements in which ground reflection occurs is shown in Fig. 5. The algorithm begins with the collection of measurements from multiple sensors. In order to calculate the threshold for the ground-reflection elimination, the lane information is required. In the first loop, there is no existing lane information. Therefore, the ground-reflection elimination is not conducted in this loop. Lane information is then estimated using the raw measurements. If the estimation result is convincing, it is used in the next loop. If it is not, the estimation is held off until additional measurements are obtained, which will be collected in the next loop. When the lane information is obtained, the algorithm calculates the threshold using the lane information. Equation (2) is used in this step. After calculating the threshold, the algorithm eliminates the measurements with values less than the threshold, which are considered to be ground-reflection measurements. In the next step, the majority-voting algorithm filters out the ground reflections that are not eliminated in the previous step. The remaining measurements can be considered as those of the distance between the vehicle and curb, and the averaged value is provided as an output of the curb detection system. This output is also used for detecting the lane in which the vehicle is driving, and this information is used for the calculation of the threshold in the next loop.

Figure 6 demonstrates the effectiveness of the proposed ground-reflection elimination algorithm. The raw measurements collected from the three ultrasonic sensors are shown in Fig. 6(a), and the estimated distance to the curb without ground-reflection elimination is indicated by a red line. A conventional moving average filter is used to estimate the distance. The measurement outliers in Fig. 6(a) are likely due to ground reflections.

The estimated distance after applying our ground-reflection elimination algorithm is presented in Fig. 6(b). The raw sensor measurements are filtered by the ground-reflection elimination algorithm. The algorithm eliminates the ground reflection and leaves only the measurements reflected from the curbs. In this case, the estimated distance is smooth and follows the trend of the filtered measurements well. Moreover, even though the algorithm eliminated the ground-reflection measurements, the system availability is not decreased in this case. In a case with more noise and external influence, the availability may be decreased after performing the algorithm, but the decrease in availability can also be suppressed with using more sensors. Therefore, availability can be retained above a certain required level even in harsher driving situations.

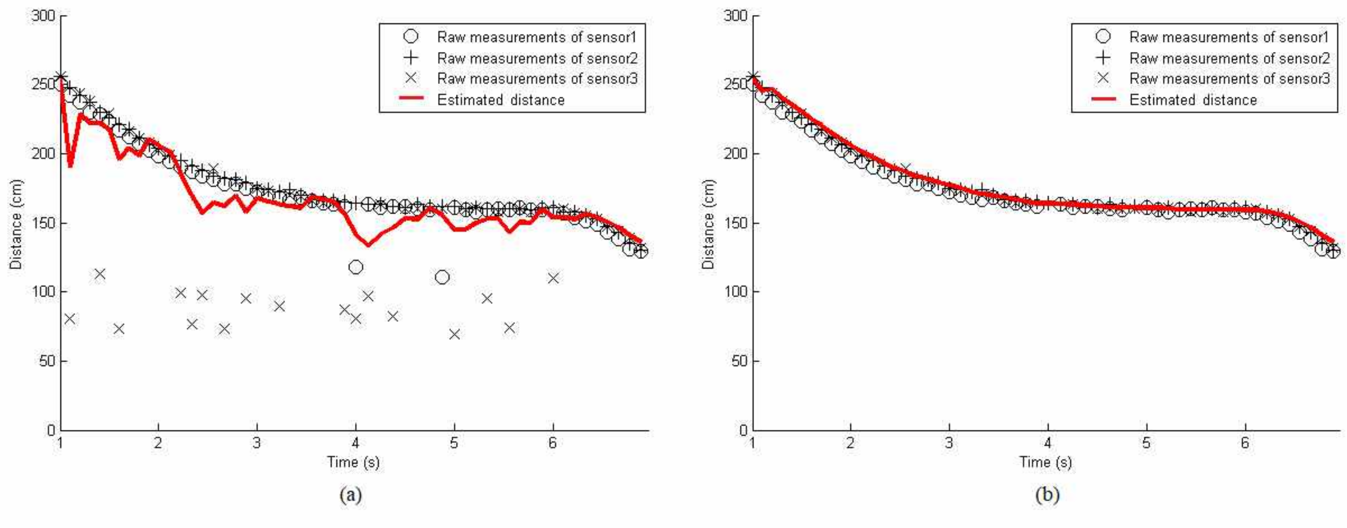

Figure 6. (a) Distance estimation result of a nominal moving average filter without ground-reflection elimination. (b) Distance estimation result of the ground-reflection elimination algorithm.

CONCLUSION

This research details the ground-reflection effect observed when using ultrasonic sensors for a curb-detection system, and presents an algorithm for eliminating it. The experiments were performed on a hardware platform that was developed in the process of this study. The developed curb-detection system was tested in various driving scenarios, and representative results of the experiments were presented in this paper. The performance of the ground-reflection elimination algorithm can be further improved by increasing the number of sensors or using higher-accuracy ultrasonic sensors. Additional improvements and experiments shall follow in future research in order to develop a low-cost curb-detection system that can be commercialized for use in common vehicles and autonomous driving vehicles.

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