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Estimation of Road Surface Height for Preview System using Ultrasonic Sensor

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***Abstract*—The vehicle industry has applied active suspension system for a long time to enhance ride-quality and driving stability. However, only a small improvement is seen in the absence of a preview sensor, and thus it is an integral component in designing active suspension systems. Devices such as stereo vision, lidar, and radar systems thus far have been used when building preview information for active suspension systems. These devices have some drawbacks, however, including costliness and the requirement of complex computations. A high performance data processing device is thus needed to compute complicated calculations in real time, which further increases costs.**

The goal of this research is to examine the use of a low cost ultrasonic sensor to compute road surface height estimation in real time by using simple algorithms.

Keywords– *road surface height estimation; low cost preview sensor module; active-suspension;*

I. INTRODUCTION

A vehicle's suspension system plays a significant role in improving ride-quality and ride-handling by maintaining the weight of the vehicle as well as stabilizing vibrations from uncertain road surfaces. However, optimizing suspension settings for both ride-handling and ride-quality is challenging because of the trade-off between these two factors. To resolve this issue, active and semi-active suspension systems have been developed.

The main problem with these approaches is the slow reaction velocity of the suspension systems actuator. This makes it difficult to control the suspension system of the vehicle in real time. The other problem is that the system is not capable of providing road surface information in advance. Both active and semi-active suspension systems cannot be optimized for all road conditions. They rather take the average road estimation, and this limits the use of these suspension systems on various road conditions. On the other hand, if the controller of a suspension system is designed such that is capable of providing information of the road ahead, optimizing the suspension system for various road conditions becomes possible.

A look-ahead sensor is used to obtain road surface information and devices such as a stereo camera [2], [4] and lidar [1], [6] are used. One advantage of using a camera system or a lidar system is that it uses light to obtain information of the road that is relatively far ahead of the vehicle. However, its performance is strongly affected by vision, and wrong information can be transmitted in certain environmental conditions. These sensors are also costly and require a high performance information processing device, which further increases the cost.

In this paper, a road height estimation strategy using a low cost ultrasonic sensor module is proposed. The ultrasonic sensor creates sound waves that are larger than 20kHz and estimates the distance by measuring the time of a sound wave being reflected from the surface. This sensor is cost efficient and its computational cost is in a competitive range. The goal of this research is to prevent a vehicle or a robot from shaking by previewing the road surface [3] using this cost efficient and high performance ultrasonic sensor module.

The remainder of this paper is organized as follows: In section II, hardware systems are presented, followed by sensor calibration in section III. In section IV, the algorithm employed for estimating the road surface is presented. Finally, this work is concluded with results in section V.

II. HARDWARE DESCRIPTION

This section introduces the sensor used for estimating the road surface height and the test environment.

A. Ultrasonic Sensor Module

The ultrasonic sensor module is composed of an ultrasonic transmitter, a receiver and a sensor controller. The ultrasonic transmitter sends a signal by vibrating a piezoelectric element. When echo of ultrasound waves vibrates the element of the receiver, the sensor module sends the response signal. Time-of-flight(ToF), which is the difference in time between transmission and reception, is used to measure the distance from

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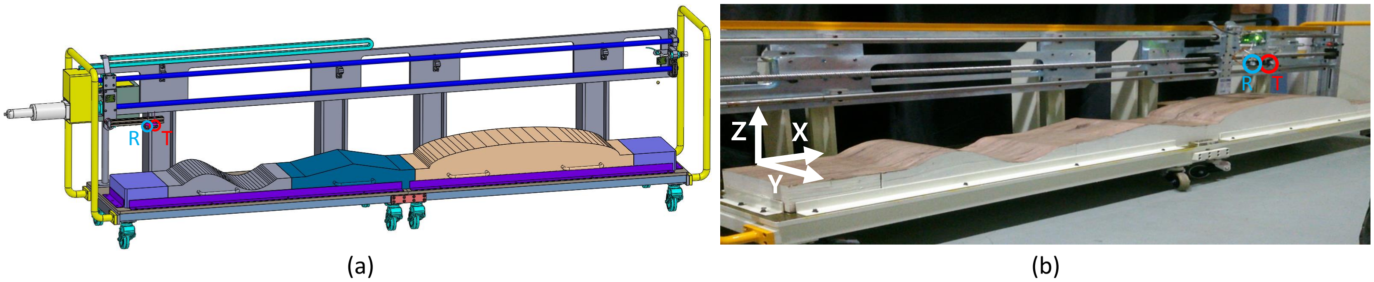

Fig. 1. (a) is the designed test bench and (b) is a real test bench prepared for this study. The test bench has a road model that is longer than three meters and thus is able to test the road height estimation sensor module in real time. In this figure, red and blue circle indicate ultrasonic transmitter and receiver.

the ultrasonic sensor. The distance traveled by an ultrasonic wave from ToF can be obtained from the following equation.

$$d = v \cdot t \tag{1}$$

d is the distance the sound wave traveled whereas the t represents the flight time. v represents the speed of a sound wave where the signal is the received environment.

Signal attenuation from the ultrasonic wave receiver and the surrounding noise make precise measurement of ToF challenging. A threshold value recognition method is used to resolve this issue. Specifically, sound waves are recognized when the wave signals amplitude exceeds a certain threshold, and this is accomplished by a sensor controller. With this method variance is still inevitable but it can be minimized when the distance and the surface angle of an object that it is targeted for recognition are determined.

In this test, the ultrasonic transmitter is installed at the front of a vehicle and ultrasonic receiver is installed directly behind of the ultrasonic transmitter as a look-ahead sensor for the suspension control.

B. *Micro-controller*

A micro-controller unit is required for controlling the ultrasonic transmitter, computing the road height from the ToF signal, and sending information to the main controller. An AT90CAN128 is used as it has controller area network (CAN bus) capability and is affordable.

Using this micro-controller, a transmission signal is sent and the road surface height is calculated periodically using the ToF signal from the ultrasonic receiver. The micro-controller is also used for sending road surface data to the main controller to control the suspension system.

C. *Road Surface Test Bench*

Figure 1 is a road surface test bench that can test and validate the performance of the sensor module described in sections A and B. The test bench includes a bumpy road shape such as sinusoidal and triangular shapes. The sensor module is installed on a vehicle that is attached to a motorized lead screw to assume a moving vehicle. The motor driver of the motorized lead screw controls the vehicles velocity and position.

III. SENSOR CALIBRATION

Even the same sensor model can differ in specific qualities, and thus sensor calibration inevitably must be performed. This section provides an explanation of the sensor calibration performed after the sensor module is installed in the test bench.

A. *Hardware Calibration*

When the transmitter sends the transmission signal one time, a maximum of 5 signals can be received, as shown in fig. 2, with a certain threshold. The very first ultrasonic signal received is the signal that came directly from the transmitter to the receiver. The second signal is the signal that is reflected from the closest road surface. Signals that come after are the reflected signals from the road surface or the surrounding environment. Therefore, it can be assumed that the signal that is required for road surface height estimation is the second signal. Accordingly, hardware is calibrated by physically changing the size of the threshold, in which the signal is recognized to be received two signals maximum.

B. *Software Calibration to Get Distance Value*

The distance can be calculated from the second signal. In a normal case, the distance can be calculated by using (1) but a low-price micro-controller or a receiver that uses the threshold value recognition method can have an offset between time and the distance. Therefore, (1) is revised as (2) and (3).

$$d = (t + t_0) \cdot v + d_0 \tag{2}$$

t_o represents the offset related to time whereas d_o represents the offset related to distance.

$$d_{1,2} = a_1 \cdot c + a_2 \tag{3}$$

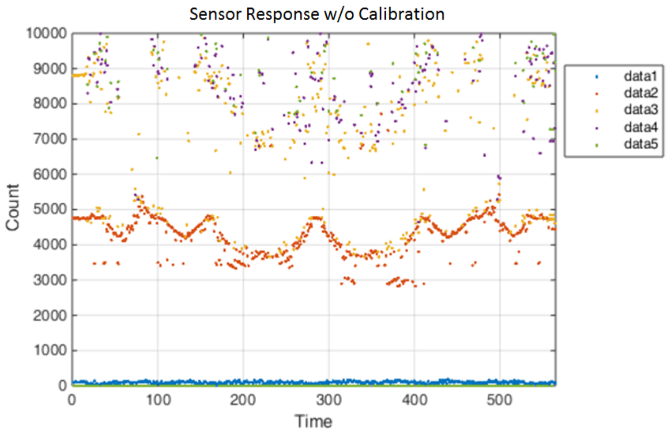

Fig. 2. received sensor interrupts when the vehicle is moving. Data 1 to 5 show multiple received signals from one transmission.

Equation (2) is modified to give equation (3) so that the calibration parameters a1 and a2 can be calculated from two known distances d_1 and d_2, which are obtained from the experiment. Here, c represents the counting time until the MCU receives a ToF interrupt after transmission.

After these calibration processes, the following neat result can be obtained.

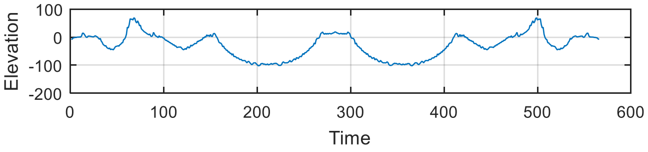

Fig. 3. Road surface height estimation result after applying calibration parameters when the vehicle is moving.

IV. Longitudinal Displacement Estimation

When the sensor module is attached at the front bottom of the vehicle, the estimated road surface value can vary depending on the vehicles speed and the moving direction because sound waves use air as a medium. Therefore, longitudinal displacement estimation is essentially required.

The distance between the sensor and the wheel axle in the longitudinal axis is constant and the time it takes to calculate the road surface height estimation is constant regardless of the vehicles velocity. Thus, the road surface height estimated point from the wheel axle in the longitudinal axis can be modeled as equation (4).

$$x = b_1 \cdot v + b_2 \tag{4}$$

v represents the vehicles speed and x represents the position difference in which the road surface height is estimated from the sensor module. b_1 and b_2 denote optimized calibration parameters. Through this equation, it is possible to calculate the longitudinal displacement for a certain road surface height in real time.

Parameters b_1 and b_2 can be derived from the sensor module output by comparing the known road surface height. THE ICP (Iterative Closest Point) algorithm [5] is used to compare two different point clouds obtained from an accurate laser sensor and the ultrasonic sensor module.

V. Experimental Results and Conclusion

Figures 4 to 7 graphically presents the performance test results of the road surface height estimation method proposed in this paper obtained with the test bench. The blue line represents the real value of the road surface of the test bench and the red dots denote road surface estimated points using the sensor module with the proposed calibration method.

The estimated value is generally higher than the real road surface height in a steep downhill road. In the ROC (Receiver Operating Characteristic) curve below, the X-axis represents the calibration tolerance whereas the Y-axis represents estimation values that are within the calibration tolerance range. For instance, when the calibration tolerance is 5mm, about 70% of the data are within the range.

AUC (Area Under Curve) is the area under the ROC curve. A larger AUC value corresponds with higher performance. The algorithm showed 1.46% to 2.84% errors in different velocities.

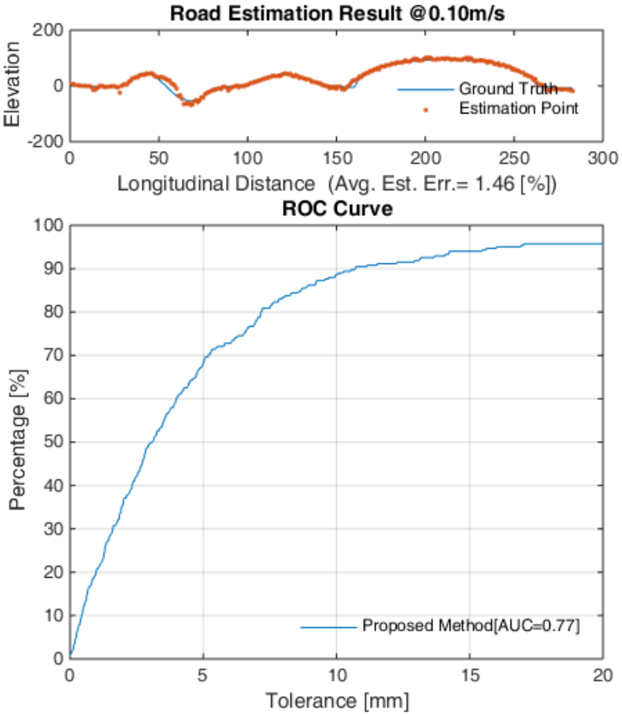

Fig. 4. Road estimation result when vehicle moves to 0.1m/s

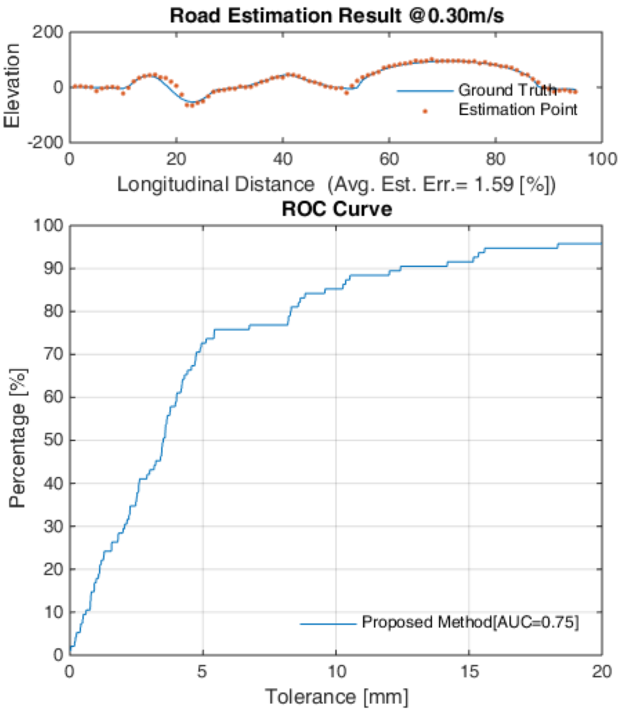

Fig. 5. Road estimation result when vehicle moves to 0.3m/s

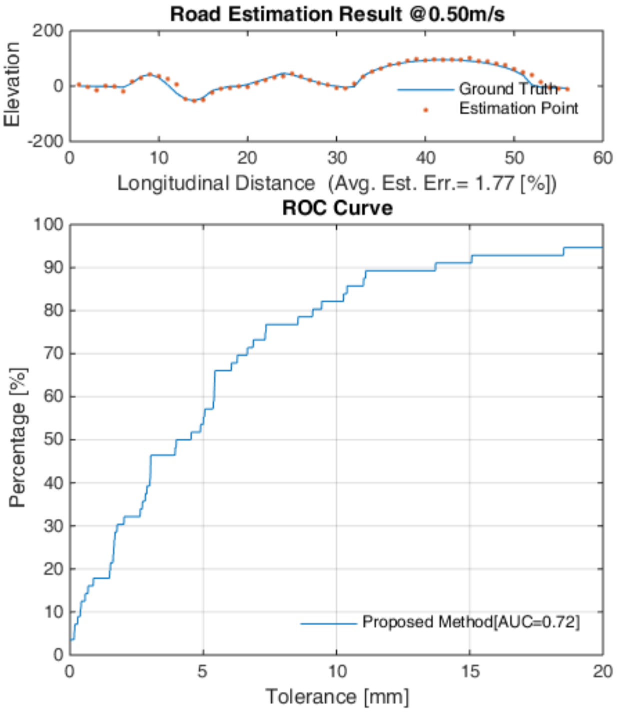

Fig. 6. Road estimation result when vehicle moves to 0.5m/s

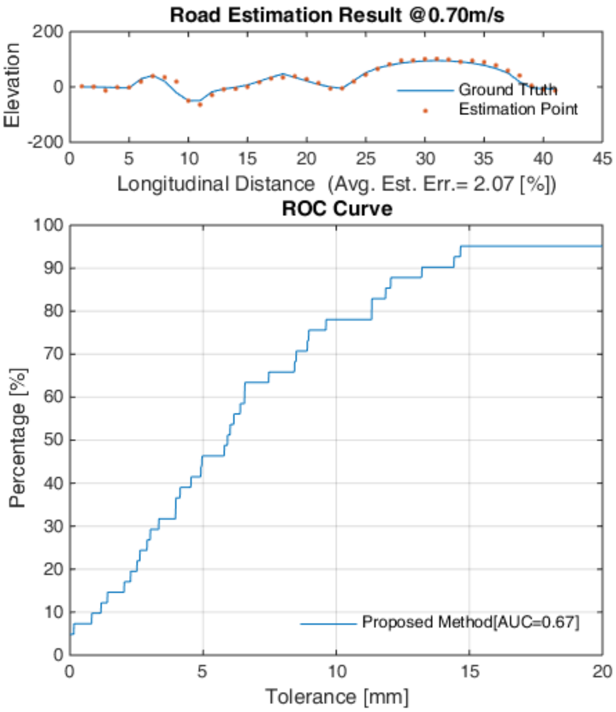

Fig. 7. Road estimation result when vehicle moves to 0.7m/s

This paper proposed and tested an algorithm that employs an affordable MCU to be used as a look-ahead sensor in active suspension. Future work will focus on producing a more robust sensor module and algorithm with an array of ultrasonic sensors to provide 3D road surface estimation to an active suspension system in various road conditions where steering also taken into consideration.

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