A Path Planning Achievement of Car Following in Motion Control via LiDAR Sensing

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Abstract*—This paper presents a new car following system to track a preceding car and maintain a desired safe distance based on a laser imaging, detection, and ranging (LiDAR) sensor. The proposed system has the ability of lane change, including longitudinal and lateral control. To accomplish the car following sensing task, environment information provided by in-vehicle Lidar and monocular vision is used. A camera is an auxiliary device to map Lidar data into the output image and verify the detection ability of LiDAR. The LiDAR and camera sensors are installed on a demonstrated vehicle, and the LiDAR sensor which has one-dimensional scanning ability can measure the relative distance of the vehicle from a preceding vehicle by scanning the horizontal plane with laser beams. The relative position is processed and estimated by random sample consensus (RANSAC) method and geometry relation, and then the heading and speed of vehicle are automatically operated by an embedded processor. The speed variation tracking is implemented by fuzzy-PI algorithm, and the pure pursuit method is applied as the steering control strategy to keep up with the trajectory in lateral control. Environmental clutter becomes the main challenge in data processing when LiDAR tries to track the desired vehicle. Besides, a comfortable requirement of vehicle control is also considered and complied with the rule of ISO 2631. Thus, the proposed system integrates engine vacuum connected to throttle and active steering system with embedded ahead control algorithms into a powerful car following system in practice, which has been verified in experiments using two vehicles. The mobile hardware are built with three embedded systems using X86 processor in Linux system, and furthermore the sensing data collection is accomplished by Ethernet interface. The proposed system is carried out with theoretical application and hardware integration, and the result shows car following approach applicability.

Keywords- LiDAR; car following system; fuzzy-PI

I. INTRODUCTION

In recent years, the number of fatalities in traffic injuries is about nearly 43 thousands according to U.S. department of transportation (DoT) statistic data and the incapacity for work of over 3 consecutive days is about 3.2 million. To solve this kind of problem, such as intelligent transportation systems (ITS) and smart car [1], are the most popular method to implement at present traffic problems with the increase of people and vehicles all over the world. In 1997s, an intelligent vehicle highway systems (IVHS) program was presented and could give a viable solution to decrease the related problems in addition [2]. Furthermore, the ITS implementation includes advanced vehicle control systems (AVCS) or automated highway systems (AHS), in which fully automated vehicles are operated on special highway lanes with support from the infrastructure in 1960s. In the AHS area, the operation of vehicles in a group with a small headway, called as platooning, was proposed for maximizing the highway capacity and passenger safety. But every vehicle needed to have three magnetometers mounted beneath the front and rear bumpers, and the markers were installed every 1.4 meters by surveying the location, drilling a hole, placing the magnets [3].

Nowadays, adaptive cruise control (ACC) is one of the popular assistant driving devices under the broad field of ITS with the objectives of increasing the capacity and improving the safety of existing highway systems [4-5]. Each vehicle is automatically only controlled in longitudinal direction under ACC operation, and the inter vehicle distance is kept small within each platoon so that the highway capacity can be increased by 2-6 times over current peak capacities [6-7]. Besides, lane keeping, i.e., regulation of lateral deviation from the road center line becomes the goal of any vehicle lateral control system. This kind of system is relied on camera recognition but it has a shortcoming about vision reliability [8-9]. In addition, a differential GPS and vision system are also combined to do lane following. Although DGPS has high precision position, its shortcoming may cause some accident result from lost positioning signals in a tunnel.

Dynamic objects, such as a vehicle, must detect the on-line condition through the use of range sensors. In order to do effectively field detection, LiDAR is considered to track preceding vehicle [10]. LiDAR which is mounted on mobile robot is become a common solution for navigation demand. This sensor also has characteristic accuracy of measurement performance, and it is possible to meet an on-line sensing. As the drivers relied on the visual perception, a camera can provide environment condition. An image data has high resolution in pattern recognition, but the camera is only adopted as mapping.

To meet an automatically control requirement, an engine vacuum mechanism is connected to throttle and controlled by pulse width control (PWM). The mechanism has three wires to control the closure percentage of engine by adjusting the inside pressure. In direction control, an encoder is adopted to measure the steering angle and feedback to steering controller. Hence, the steering angle could be compared with reference command and actuated by a motor.

In this paper, the proposed system uses three embedded systems to operate as a car following system and to manipulate LiDAR, camera, throttle and steering for following the preceding vehicle. A camera is adopted and the scanning data of LiDAR are mapped into image data. From LiDAR information, the relative position is calculated and tracked by converting to a curve equation. The throttle is adopted as a speed control actuator in longitudinal direction and steering is used to do lateral variation control.

II. The Concept of Car Following System

The system technology for car following system is designed with an integration of camera and environment sensing through LiDAR [11]. The range sensing information may be mapped and display on image to show the driving appearance in on-line operation. The LiDAR also shows the road two-side condition, and the sensing data can display object's shape by applying linear regression method. In vehicle dynamic information, vehicle speed is captured by calculating wheel displacement relative to controller trigger time. The architecture of the proposed system is shown in Figure 1 below.

A. *The proposed System Architecture*

A data fusion of car following system platform is built of the basic three parts, including camera, LiDAR, and actuator devices. All of the platform systems adopted X86 processor as the mainly core, where the embedded kernel to access data input and output is programmed. To fulfill the proposed tracking application, image data as well as LiDAR data are processed in specific handshakes, digital formats and sent through video terminal and non-synchronous serial interface. In the left part of Fig. 1, each part's microcontroller has its responsibility to communicate with microprocessor. Each microcontroller transmitted commands to terminal device or received feedback signals. Meanwhile, each processor is activated and used as coordinator by embedded Linux system. In data acquisition, the timing procedures are well-design by frequency division. For this reason, all of the sensing data is accessed by port selection.

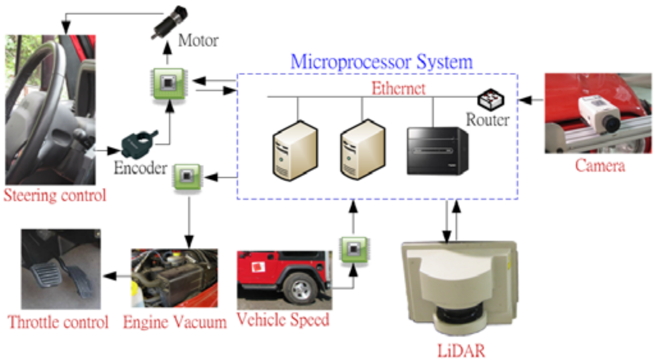


Figure 1. The proposed system architecture.

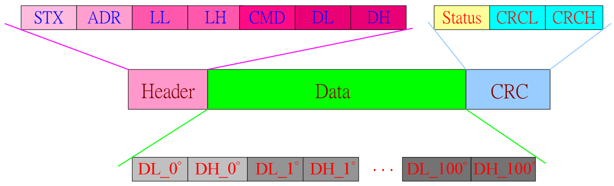


Figure 2. LiDAR format.

Figure 3. LiDAR and its interface.

B. *LiDAR Unit*

Due to have greatly ability in rebuilding some objects, such as airplane accident in 3-D reconstruction, LiDAR technology has become a dominant technology in shape construction. Urban challenge is another application and this sensor is used to provide data on the surrounding environment for obstacles avoidance and mapping. In this proposed system, the adopted sensor has three kinds of interfaces, including RS-232, RS-422 and CAN interface. The second interface was selected and the communication baud rate is set at 50000 bps, 8N1 protocol. In system implementation, the procedure of message exchange included three steps: initial, handshake and data acquisition. After the sensor initiation, the received data format is shown in Fig. 2 and the data sizes are depended on the assigned resolution. The total sizes of header and checksum codes are 10 bytes, and the data lengths of proposed system are 401 bytes in 0.25 degree separation. The header describes start bytes, PC address, total lengths, command, data sizes, status and checksum code. Fig. 3 is the device and its interface.

C. *Camera Unit*

For driver requirement, a CCD camera is adopted in this system and mounted in the outer frame of car. In application, the camera work is only assistant surrounding display after the decoding process from NTSC analog format to ITUR-656 digital format. The Y signals of color space are addressed to mapped LiDAR data so that the processed image is displayed. Besides the sight angle of selected CCD is also considered and approximately tied in detecting angle of LiDAR.

D. *Actuator Unit*

The actuator is divided into three parts, including throttle, steering and wheel speed estimation. The throttle is controlled by an engine vacuum, as shown in Fig. 4. The PWM method is applied to adjust the pressure of engine cavity by A, B and C circuit. And the steering angle variation is accomplished by motor control and the feedback sensor is made by Bosch. The last part provided the vehicle speed to the embedded core with using hall sensor detecting in Fig. 5. The sensing technology used two interrupts. One interrupt is a counter to get the numbers of wheel perforation. Compared with the trigger time, the other interrupt is used to read the counter value and calculate the speed.

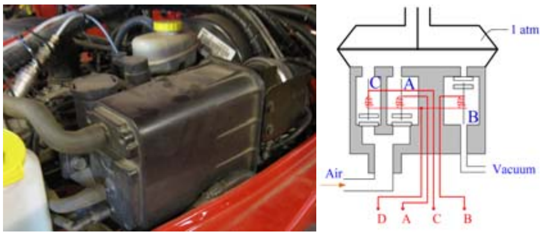


Figure 4. Throttle control mechanism.

Figure 5. Wheel speed detection.

III. CAR FOLLOWING ALGORITHM

To keep up with the preceding car, three kinds of algorithm are embedded inside the microprocessor. One algorithm is used to integrate the LiDAR and camera information, and that needed to do camera calibration before using the camera device. After discriminating the preceding car position, the following procedure comprised the other two algorithms to control vehicle speed and tracking trajectory.

A. LiDAR and Image Integration

The camera was used as image source in car following system after the calibration had been finished. It meant that these internal parameters and external parameters had obtained, including lens distortion vector (k_C), principle point (cc), focal length (f_C), skew coefficients ($alpha$), rotation matrix (${}^{C}_{W}R$) and translation matrix (${}^{C}O_W$). The index "c" is camera coordinate and other index "w" means world coordinate system.

When LiDAR measured environment condition, these sensing points were translated from LiDAR coordinate to world one in Fig. 6. The extrinsic parameters were provided by geometry relation, and then these ahead processing points were proceeded to camera one by (1) [12]. In addition, these LiDAR points would be normalized by z-axis value in (2). Before the range data mapped into image, each normalized data would use (3) to operate distorted compensation. Equation (4) is the mapping matrix which provides coordinate transform into image frame.

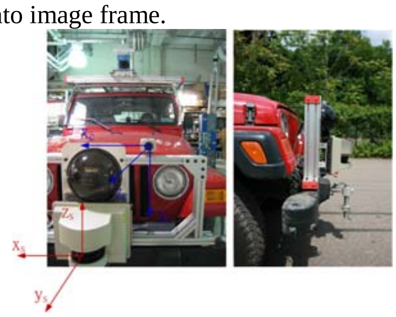


Figure 6. LiDAR and camera coordinate systems.

$$\begin{bmatrix} P \\ 1 \end{bmatrix} = \begin{bmatrix} R & {}^{C}O_W \\ O^T & 1 \end{bmatrix} \begin{bmatrix} P \\ 1 \end{bmatrix} \quad (1)$$

$$x_n = \begin{bmatrix} X_C / Z_C \\ Y_C / Z_C \end{bmatrix} \quad (2)$$

$$x_d = (1 + k_C(1) r^2 + k_C(2) r^4)\, x_n \quad (3)$$

$$\begin{bmatrix} x_p \\ y_p \\ 1 \end{bmatrix} = \begin{bmatrix} f_C(1) & alpha \times f_C(1) & cc(1) \\ 0 & f_C(2) & cc(2) \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_d(1) \\ x_d(2) \\ 1 \end{bmatrix} \quad (4)$$

B. Fuzzy-PI Algorithm in Throttle Control

This system also provided a speed tracking function by following current distance. The control strategies contain speed up, tracking and throttle release in Fig. 7. Furthermore, the suffix "c" means current condition and the other suffix "d" is desired time. An example is helpful to explain the speed tracking. If the speed of preceding vehicle is 40 km/hr and own speed is 10 km/hr, vehicle will use speed classify to do speed up. The speed classify method is obtained from fixed throttle tests, and the acceleration of speed operation is below the maximum of ISO2631 with a comfortable driving. When own speed is close to target speed about 30 km/hr, the accelerated method is changed to Fuzzy-PI method by well-designed rule table and experienced PI gains [13-14]. If vehicle speed is over 45 km/hr, the closure percentage of throttle will be released. For the safe operation and doing experiments, the brake control is operated by driver.

According to the previous discussion, the input parameters are speed error and error summation. Each membership function is composed of three triangular curves in central position, and both sides are trapezoid relations. The fuzzy table is shown in Table I, where the control gain uses the same as table. In defuzzification step, it uses center of gravity and the control gains are required and shown in (5) & (6). If the output rate of actuation was too small and control gains were not selected well, the proposed system had some damping appearance from the vehicle speeded up or slowed down. Besides, the desired speed is calculated from rule and it is calculated by 3rd curve fitting in (7).

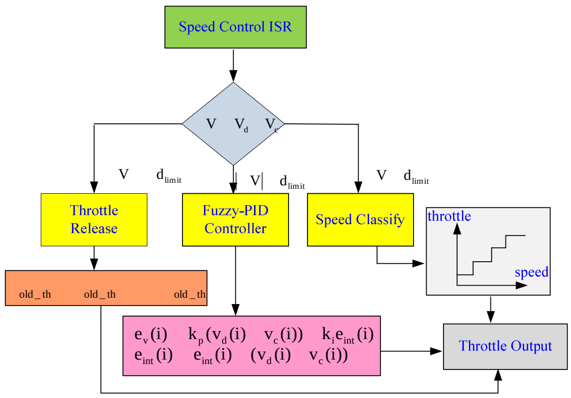


Figure 7. The flowchart of throttle control.

Table I. Fuzzy Table of K_P and K_I.

K_P/K_I		e				
		NB	NS	ZR	PS	PB
Error sum	NB	NB	NB	NS	NS	PB
	NS	NS	ZR	NS	ZR	PS
	ZR	NS	NS	ZR	PS	PS
	PS	NS	ZR	PS	ZR	PS
	PB	NB	PS	PS	PB	PB

$$K_p = \{2.2/NB, 1.6/NS, 1.2/ZR, 1.8/PS, 2.5/PB\} \tag{5}$$

$$K_I = \{0.2/NB, 0.12/NS, 0.08/ZR, 0.15/PS, 0.22/PB\} \tag{6}$$

$$V_d = 16.282 + 2.338 ? d_k \quad 0.02 \quad d_k^2 \tag{7}$$

C. *Pure Pursuit in Steering Control*

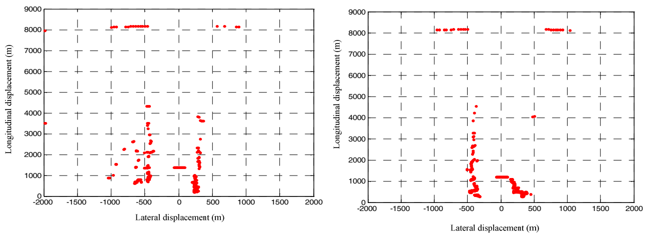
After the LiDAR provided its sensing data, that needed a search work to reach the car following requirement, as shown in Fig. 8. The simple RANSAC method was used in this paper, and the post-processing result would find the preceding car and its width. In this paper, the strategy was to decide the calculated width if it was located in the reasonable range. From the car manufacturer, the width of preceding car is about 169 cm in the experiments. The reasonable range would be located between 145 cm and 197 cm from static tests which the preceding vehicle was stopped at a distance of 15m to 40m ahead.

The following step is to meet a smooth radius of car turning, as shown in Fig. 9. From geometry relation, the turning radius could be expressed in target's position [15], as shown in (8). Moreover, the radius presented as wheel angle (j_s) with reference to turning mechanism in (9). The "w" is own width and the parameter "r" is curvature.

$$r = \frac{L^2}{2x} \tag{8}$$

$$j_s = N\cot^{-1}\left(\frac{1/r + W/2}{L}\right) \tag{9}$$

where w: car width, r : curvature, N:gear ratio.



(a) Condition 1 (b) Condition 2

Figure 8(a) & 8(b). Preceding car searching for different conditions.

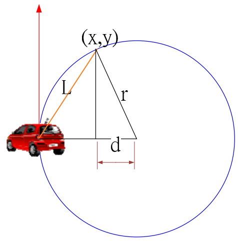


Figure 9. Pure pursuit tracking.

IV. VERIFICATION TESTS

Two vehicles are used to implement the proposed on line car following system. The front car is used to be tracked, and moreover, the rear car is used to operate car following concept and verify the proposed function capability. Under system design and implementation, integrated control algorithms are well-design and installed on the vehicle processor for tests as follows. For test operations, the brake control is reserved to switch into human operation in case of back-up interruption being necessary.

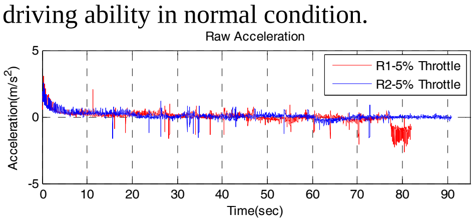
Fig. 10 shows several fixed throttle test from 5% to 20%, where the vehicle ran on Carnegie Mellon University campus. This vehicle direction was controlled by driver, and the throttle was fixed in desired closure. The speed variation offered important awareness to the vehicle under test, and therefore the acceleration would be known by curve fitting method among throttle, speed and acceleration. The sampled throttle data was collected once every 0.01 seconds periodically through Ethernet interface. R1 and R2 respectively show the first raw data and the second raw data. The data which showed some ripple was inevitable, but it was not a problem in this paper. The 3rd curve fitting method could smoothly calculate the function how this vehicle was tested in on line performance of motion conditions. Based on the ISO2631 rule, a fairly comfortable acceleration is approximately under 0.63 m/s^2. The acceleration method would be embedded and applied in the system controller.

After the acceleration of vehicle performance was obtained and used as the speed classify, the following step was to do speed tracking test. Fig. 11 showed the acceleration progress from stop to desired speed, and there are two figures which was shown the accelerated robustness that human kicked brake. After the speed slowed down and human released bake, the speed would accelerate close to desired speed. Sometimes this function is called as adaptive cruise control.

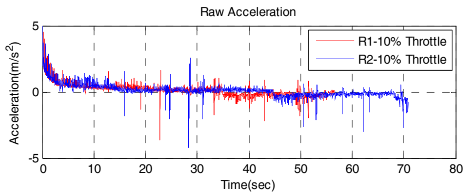
For test operations, LiDAR and camera integration test is used to do control strategy. The embedded system did data integration and tested the ability in express way, as shown in Fig. 12. The test examples were the LiDAR points onto the image space. The result offered drivers to know current condition with other vehicles or obstacles. A driver usually has little attention in distance relative to other vehicles, and this map is usually called as driving environment map.

In real car following operation, the image data is only used for display and LiDAR points are provided to calculate speed and minimum distance of preceding vehicle. Fig. 13 showed the car following implementation, and the front car is located and calculated by LiDAR sensing. After LiDAR built the environment map, the microcontroller gave the relative position and the target speed. The throttle would accelerate or release the throttle by embedded algorithms. The relative position was used to calculate the turning curvature, and therefore the steering would do a wheel angle control.

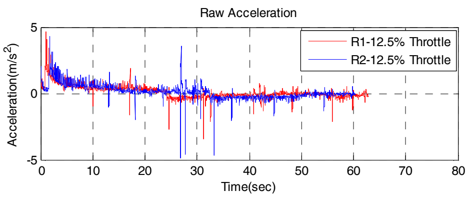
The demonstrated vehicles are tested at speed of 15~35 km/hour. From speed and turning tracking characteristics, the test experiment gave a concept about lane change and car flowing. However, in the tests, the proposed system had verified to low speed control under 35 km/hr for effective tracking. The test result can be provided to higher speed to enhance driving ability in normal condition.



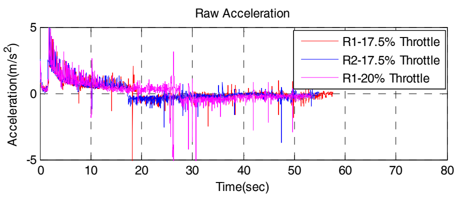
(a) Fixed throttle with 5%



(b) Fixed throttle with 10%

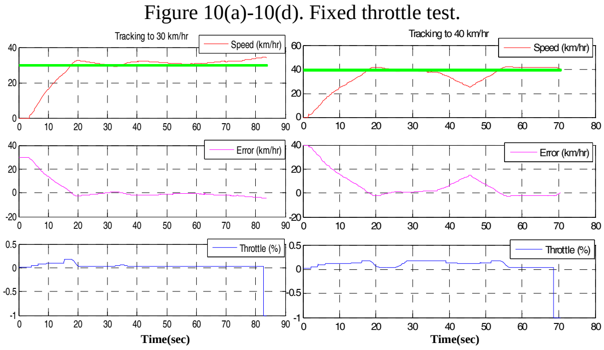


(c) Fixed throttle with 12.5%

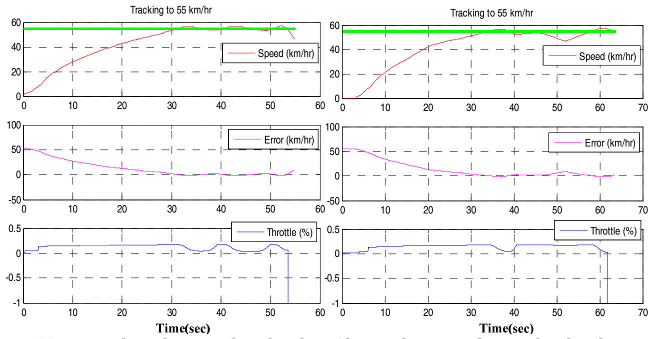


(d) Fixed throttle with 17.5%

Figure 10(a)-10(d). Fixed throttle test.

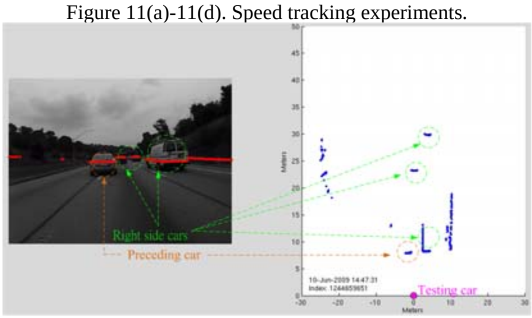


(a) Desired tracking with 30km/hr (b) Break test with speed 40km/hr

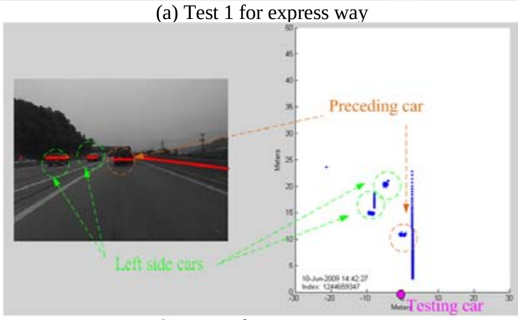


(c) Desired tracking with 55km/hr (d) Break test with speed 55km/hr

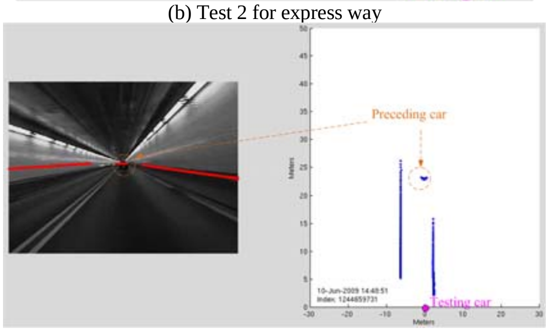
Figure 11(a)-11(d). Speed tracking experiments.



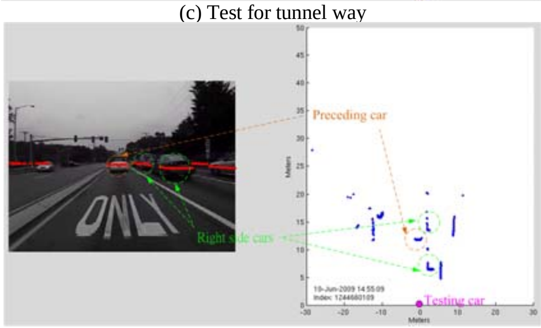
(a) Test 1 for express way



(b) Test 2 for express way



(c) Test for tunnel way



(d) Test for general road

Figure 12(a)-12(d). LiDAR and camera integration tests.

(a)Host car and preceding car (b) steering turn right

(c) steering holding (d) steering turn left

Figure 13(a)-13(d). Car following system implementation.

V. CONCLUSIONS

In this paper, the capability of a car following system using LiDAR is verified. The proposed system designed and implemented an integrated technology using microprocessor to accomplish environment map by adding camera module through data mapping. The implementation presented the capability of the sensing information into on-line car following applications in express way or high way.

The verification tests have proven that the advantages of LiDAR and camera integration between vehicles following. This function also may satisfy most group tour and decrease the limited traffic space using safe distance separately. The proposed car following system can assist drivers to have a safe driving condition on the express way or high way with the driving situation awareness capability. The advantage of the car following system has presented with exact awareness of environment map, and the demonstration provides a feasible solution for driving control to enhance driving safety.

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