Map Free Lane Following based on Low-Cost Laser Scanner for Near Future Autonomous Service Vehicle

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Abstract— **This paper proposes a map free lane following solution based on low-cost 2D laser scanners for Autonomous Service Vehicle to fill the gap between future driverless car and the lane keeping assistant. The applications of autonomous service vehicle include feeder bus in a local residential area, shuttle bus in a park or playground, sprinkler car, sweeper car, and transporter in airport or container terminal. As autonomous service vehicle is running only in a limited area and its speed is slow compared to normal vehicles, we can further simplify the problem regardless of the issues of road infrastructure detection/communication and V2I maps which prevent the popularization of driverless car, and to propose a unique map free solution. The features of our approach include: 1) an innovative configuration for two 2D laser scanners to detect the lane with sharp curve; 2) a fast and accurate lane detection algorithm based on 2D laser's raw date directly; 3) a reliable and smooth path planning based on local lane fitting and prediction; and 4) a self-built unique drive-by-wire system for electronic car. We successfully tested our vehicle with autonomous driving in the testing field. The experiments show that the vehicle's trajectory matched the planned path accurately.**

I. INTRODUCTION

While Google, some universities and automobile companies are doing or starting up their Autonomous Vehicle projects for the future driverless car [1], [2], the major automobile companies propose the lane keeping assistant [3] to help the driver stay within the intended lane for a relaxed and pleasant driving experience, such as Škoda's Lane Assistant [4] and Toyota's Lane Keeping Assistant [5].

The lane keeping assistant usually relies on one camera to detect the lane markers ahead of the vehicle. Thus there are many limitations. The lighting condition is very important for the camera to distinguish the lane markers, so it will not work in many cases such as driving towards a low sun which occurs very often. The lane keeping assistant also doesn't work when the lane curve is sharp or the car speed is low because its steering and throttle controllers are very simple to handle these complex control situations, in fact, they are very common situations.

The objective of our research and this paper is to fill the gap between the future driverless car and the lane keeping assistant, and to propose a solution for the driverless Autonomous Service Vehicle (ASV) which can be popularized in the near-future before the future general driveless car. The applications of autonomous service vehicles include but are not limited to feeder bus in a local residential area, shuttle bus in a park or playground, sprinkler car, sweeper car, and transporter in airport or container terminal.

For the future general driverless car, many approaches have been proposed [1], [2], [6], and many sensors have been proven valuable and essential in these approaches, such as GPS+IMU for localization and lidars including Velodyne or IBEO LUX for lane detection and mapping. However, there are still many issues which need future development before the on-road popularization of driverless car, such as the detection of road infrastructure including traffic light and traffic signs. To deal with these problems, the wireless Vehicle-to-Infrastructure (V2I) communication has been proposed to exchange the critical safety and operational data between vehicles and road infrastructure [7]. And the HD Map was proposed to contain the infrastructure informations on top of the standard map [8].

Definitely, the approaches of driverless car can be used for autonomous service vehicle. However, autonomous service vehicle is running only in a limited area, and usually its speed is slow compared to the personal car and other normal vehicles, thus we can further simplify the problem regardless of the issues of infrastructure and map, and propose a unique map free solution based on low-cost laser scanners to popularize the autonomous service vehicle as soon as possible. Here *low-cost* means we just use the 2D laser scanners for the applications of autonomous service vehicle, which is much cheaper than the 3D lidars including Velodyne[1] or IBEO LUX for future driverless car.

The features of our approach include:

- An innovative configuration for two 2D laser scanners to detect the lane with sharp curve.
- A fast and accurate lane detection algorithm from the 2D laser raw data directly rather than from the 2D/3D map built by lasers.
- A reliable and smooth path planning based on the local lane fitting and prediction.
- A self-built unique drive-by-wire system for electronic car.

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[1]Velodyne released a news that a cheap 16-layers Velodyne is ready for pre-order [9]. Actually, our approach is also applicable to 3D lidars and we will test it further when it is on market.

The rest of this paper is organized as follows. First, the sensor configuration and discussion of different lane situations for autonomous service vehicle are presented in section II. Next, section III proposes the system architecture for autonomous service vehicle, lane detection based on 2D laser's raw data, and map free lane following algorithms. Then, the experiments and discussions on our testing vehicle with our self-built drive-by-wire system are illustrated in section IV. Finally, section V lists the conclusion and our future work.

II. SENSOR CONFIGURATION

A. 2D Laser Scanners

As mentioned in section I, the autonomous service vehicle is usually running in a limited area and its speed is slow compared to other vehicles, then we can simplify the problem regardless of issues of infrastructure and map and use low-cost 2D laser scanners rather than the expensive 3D lidars for autonomous service vehicle, e.g., we use SICK LMS151 2D laser scanner which is much cheaper than Velodyne or IBEO LUX.

Based on 2D lidars, some research groups use Simultaneous Localization and Mapping (SLAM) for autonomous vehicle for research purpose [10]. However, based on our survey, none of the current approaches can perform consistent maps for large areas, mainly due to the increase of the computational cost and due to the uncertainties that become prohibitive when the scenario becomes larger [11].

Furthermore, the map built by SLAM can not be used for path planning of autonomous vehicle directly if the lane markers and road curbs are not extracted. Thus, we present a fast and accurate lane detection method to extract the lane markers and road curbs from the 2D lidar's raw data rather than from the SLAM map to reduce the computational complexity and improve vehicle response in the vehicle's embedded computer.

The 2D laser is usually mounted on the top of the vehicle to look forward and look down a litter bit, thus there is a laser scanning section line on the road as shown in Fig. 1a. However, this kind of laser configuration will not fully work for the road with sharp curve as shown in Fig. 1c. Fig. 1d shows the detection result in which part of the curbs can not be detected and this may cause the vehicle to hit the curb based on such an incomplete curb detection result and the correspond path plan.

Our innovative laser scanners configuration is illustrated in Fig. 1b, in which the laser section line is not parallel to the lateral line of the vehicle, but there is a big angle between the laser section line and the lateral line of the vehicle. In this case, we will need two 2D laser scanners to take care of both the left and right sharp curves. Fig. 1e shows the detection result for the example sharp curve based on our laser scanner configuration, in which the whole inner curbs are detected.

To get the specific angle α_l between the laser section line and the lateral line of the vehicle, there needs a non-zero roll

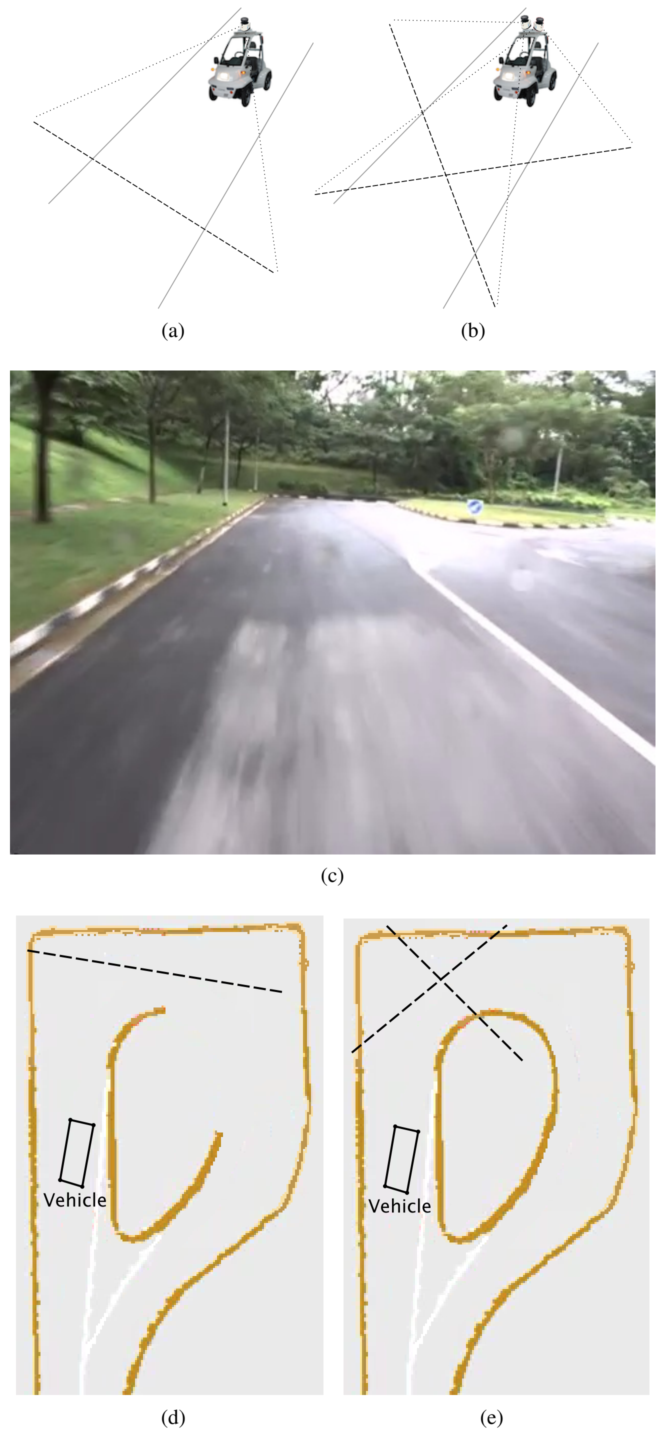


Fig. 1: 2D laser scanners configuration for sharp curve road. The dashed line is the laser section line on road. (a) Single laser looking forward and downward a little bit. (b) Our innovative laser configuration to detect the lane markers and curbs for sharp curve road as well as the normal straight road. (c) An example of sharp curve road, and no markers during the sharp curve (round-about area). (d) Part of the curbs will be missing for the laser configuration in (a). (e) Whole inner curb is detected for our laser configuration in (b), where white line represents the lane marker on road and brown curve represents the road curbs.

angle ψ_l of the laser's orientation, and which depends on the yaw angle ϕ_l and pitch angle θ_l of laser's orientation.

If the laser's position is (x_l, y_l, z_l), the laser's scanning plane function $Ax+By+Cz+D=0$ relative to the vehicle's coordinate can be calculated as in (1) and (2) below,

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} \mathrm{c}\,\theta_l\,\mathrm{c}\,\psi_l & -\mathrm{c}\,\phi_l\,\mathrm{c}\,\psi_l + \mathrm{s}\,\phi_l\,\mathrm{s}\,\theta_l\,\mathrm{s}\,\psi_l & \mathrm{s}\,\phi_l\,\mathrm{s}\,\psi_l + \mathrm{c}\,\phi_l\,\mathrm{s}\,\theta_l\,\mathrm{c}\,\psi_l \\ \mathrm{c}\,\theta_l\,\mathrm{s}\,\psi_l & \mathrm{c}\,\phi_l\,\mathrm{c}\,\psi_l + \mathrm{s}\,\phi_l\,\mathrm{s}\,\theta_l\,\mathrm{s}\,\psi_l & -\mathrm{s}\,\phi_l\,\mathrm{c}\,\psi_l + \mathrm{c}\,\phi_l\,\mathrm{s}\,\theta_l\,\mathrm{s}\,\psi_l \\ -\mathrm{s}\,\theta_l & \mathrm{s}\,\phi_l\,\mathrm{c}\,\theta_l & \mathrm{c}\,\phi_l\,\mathrm{c}\,\theta_l \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad (1)$$

$$D = -[x_l \;\; y_l \;\; z_l] \begin{bmatrix} A \\ B \\ C \end{bmatrix} \quad (2)$$

where c and s denote cos and sin, respectively.

Then the laser's section line function $Ax + By + D = 0$ on road is known, and the angle of the section line relative to the lateral direction of vehicle is

$$\alpha_l = \arctan \frac{B}{A}. \quad (3)$$

Solving the equations above reversely, the roll angle ψ_l can be derived as below,

$$\psi_l = \arctan \frac{\sin \alpha_l \cos \phi_l \sin \theta_l + \cos \alpha_l \sin \phi_l}{\cos \alpha_l \cos \phi_l \sin \theta_l - \sin \alpha_l \sin \phi_l} \quad (4)$$

B. Gyro & Encoder

In this work we focus on map free solution for autonomous service vehicle, the global localization sensor is not necessary, such as GPS. For the local localization, one gyro and one wheel encoder are enough to get vehicle's velocity and odometry.

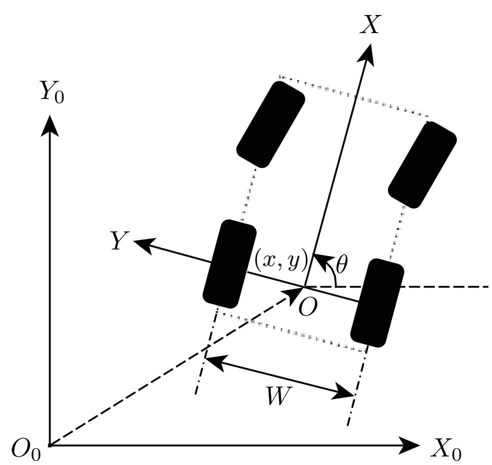


Fig. 2: Axises of odometry and vehicle. X_0-O_0-Y_0 is the axis of odometry, X-O-Y is the axis of vehicle, (x, y) is the position of vehicle, θ is the orientation of vehicle, and W is the width between left and right rear wheels.

Fig. 2 shows the axises of odometry and vehicle. We mount an encoder on left wheel and the gyro on the top center of rear wheels, then the velocity v and odometry (x, y, θ) can be updated from (5)-(8) as below,

$$x \leftarrow x + v\Delta t \cos\theta \quad (5)$$

$$y \leftarrow y + v\Delta t \sin\theta \quad (6)$$

$$\theta \leftarrow \theta + \omega\Delta t \quad (7)$$

$$v \leftarrow v_e + \omega W/2 \quad (8)$$

where Δt is the cycle time, angular rate ω is the output of the gyro, and left wheel's velocity v_e is the output of the encoder.

III. MAP FREE LANE FOLLOWING SOLUTION

A. System Architecture

Fig. 3 illustrates our system architecture for the map free 2D laser scanner based autonomous service vehicle. As described in section II, two 2D laser scanners are used to detect the lane markers, road curbs, and obstacles on the road; one gyro and one optical encoder are used to get vehicle's velocity and odometry.

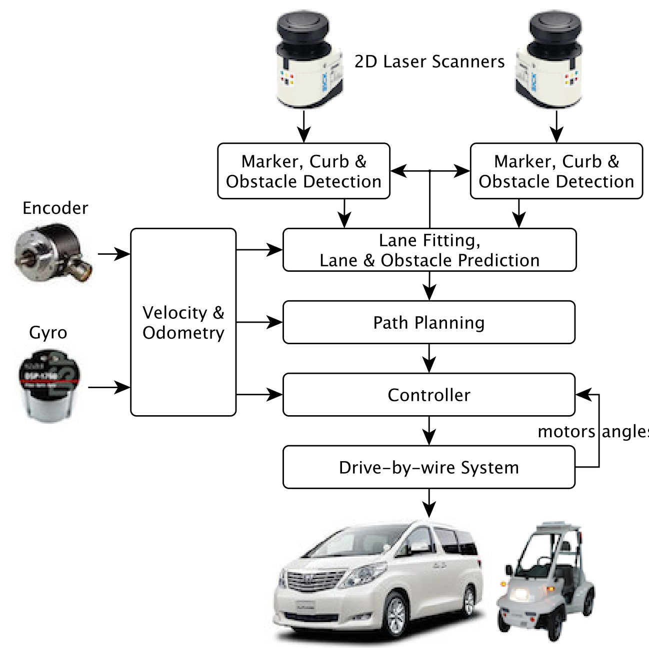
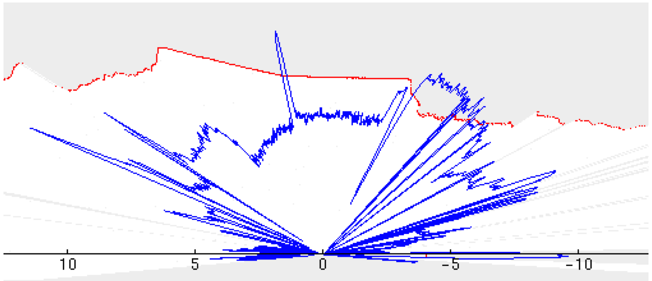


Fig. 3: System architecture for the map free 2D laser scanner based autonomous service vehicle.

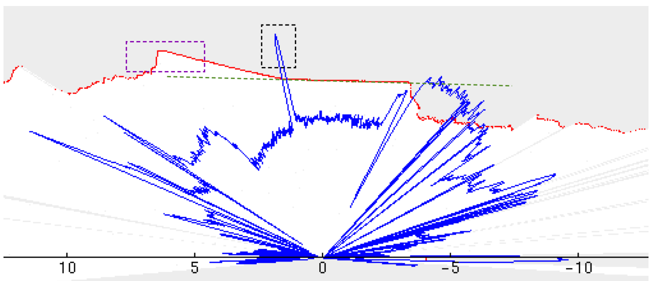
B. Lane Detection based on 2D Laser's Raw Data

Fig. 4a shows the raw data from the 2D laser scanner, which contains the depth data in red and the intensity data in blue. It is clear that the road is not flat but the middle portion is higher than two sides. Thus we can not simply use the object's height to detect the curbs or obstacles.

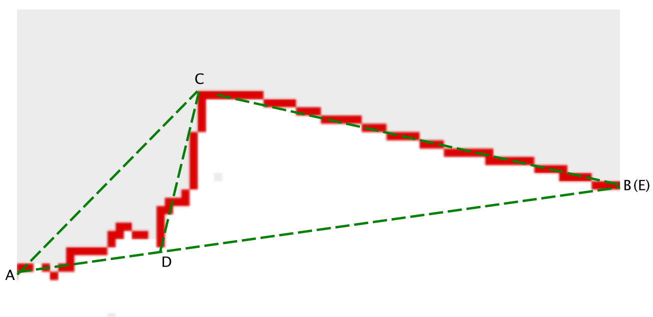
Assuming the current vehicle tyres contact with the lane's plane is flat during the calibration, then the green dashed line in Fig. 4b is the laser's section line on flat road. And the pitch and roll angles of the laser's orientation can be calibrated



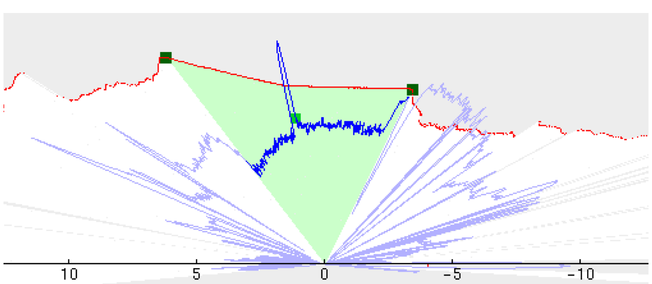
(a) 2D laser's raw data in laser's coordinate. Red curves represent the depth data and the blue curves represent the intensity data.



(b) Green dashed line is the laser section line on the flat road for laser's pose calibration, purple dashed box contains the interesting area for road curb, and back dashed box contains the interesting areas for lane marker.



(c) 2D Convex angle for curb detection.



(d) Two lanes are detected from the raw data. Green point is the detected lane marker, dark green points are detected curbs, and the light green area is the road range.

Fig. 4: Laser's raw data and detection result.

automatically from this line. The calibration equation for pitch θ_l is listed as below,

$$\theta_l = \arcsin \frac{z_l}{d_l} \tag{9}$$

$$d_l = \left| \frac{C_l}{\sqrt{A_l A_l + B_l B_l}} \right| \tag{10}$$

where d_l is the distance between the original point to the section line $A_l x + B_l y + C_l = 0$ in laser's coordinate. The roll angle's calibration is a recursion in two steps:

1) Get the new roll angle ψ_l from (4) with $\alpha_l = \arctan(B_v/A_v)$ (initially $B_v = B_l$ and $A_v = A_l$);
2) Transform section line function $A_l x + B_l y + C_l = 0$ to $A_v x + B_v y + C_v = 0$ in the vehicle's coordinate according to laser's pose.

We use 2D convex angle for the curb detection. For a detection window $[A, B]$ as shown in Fig. 4c, the detection procedure is listed in Algorithm 1, in which the obstacle is also detected with different criteria, where $c_{\min}$ and $c_{\max}$ are the minimal and maximal threshold parameters for the curb.

Algorithm 1: Curb & obstacle detection based on 2D convex angle detection.

```
Find the fastest convex angle ∠ACB w.r.t line AB
Find the fastest concave angle ∠ADC w.r.t line AC
Find the fastest concave angle ∠BEC w.r.t line BC
Calculate the heights z_D, z_C, z_E w.r.t laser's pose
if (c_min ⩽ z_D − z_C ⩽ c_max) ∧ (|z_C − z_E| < c_min) then
    Return left curb is at C
if (c_min ⩽ z_E − z_C ⩽ c_max) ∧ (|z_C − z_D| < c_min) then
    Return right curb is at C
if (z_D − z_C ⩾ c_min) ∨ (z_E − z_C ⩾ c_min) then
    Return obstacle is at D or/and E, respectively
else
    Return no curb or obstacle
```

After the curbs are detected, the intensity data which is out of road can be filtered out as shown in light blue in Fig. 4d, then the lane marker can be detected easily by the peak of the intensity data.

C. Path Planning based on Lane Fitting and Prediction

For every detected curb or lane marker, we attach the current odometry to it, and save it to the history memory, based on which the lane can be fitted by a straight lane fitting or an arc fitting piecewisely after a certain time or the vehicle passed through a certain distance. Fig. 5 shows an example of lane marking (marker or curb) fitting. The lane prediction depends on the application of autonomous vehicle. For autonomous sweeper vehicle, it always keep a certain distance to left marking. For feeder bus or transporter, the lane prediction is the rules below.

- If both left and right piecewise lane markings (marker or curb) are staight lines, then lane prediction is the center of the left/right lane marking.
- If one side or two sides of piecewise lane marking is/are (an) arc(s) fitting, then the vehicle keeps the distance to the sharper curve.

Path planning is a real-time smoothing process from the vehicle's odometry to front V-point in the lane prediction, as shown in the green solid line in Fig. 5. When an obstacle

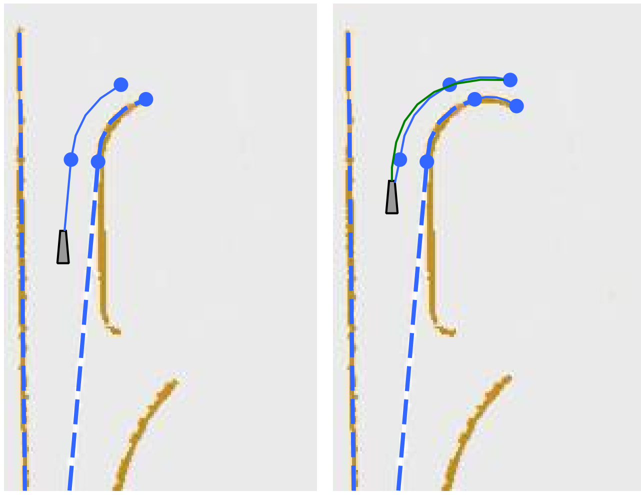


Fig. 5: An example of lane fitting and prediction, where blue point is V-point, blue dashed line is piecewise lane marking (marker & curb) fitting, blue solid line is piecewise lane prediction, and green solid line is the real-time path smoothing.

is detected, autonomous service vehicle can be just stopped conveniently. Anyway, map free obstacle avoidance is our future work.

D. LQR Controller

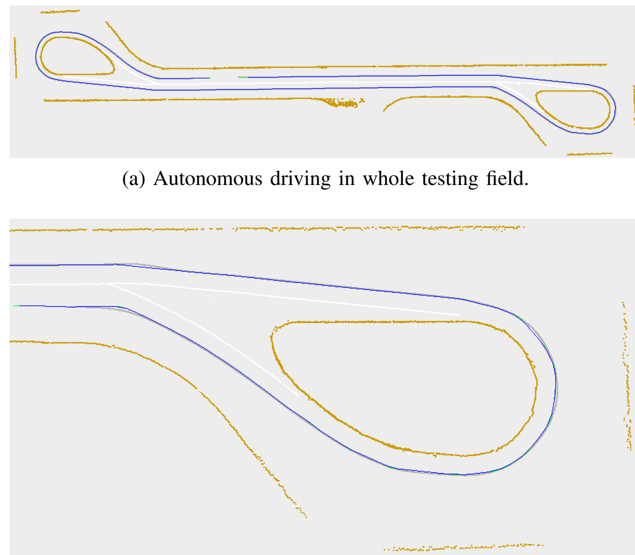
For motion control, many works have been demonstrated in literature, such as geometric pure suite controller [12], Stanley method [13] and kinematic model based controller [14]. In this paper, a bicycle model [15], [16] is used to model the vehicle dynamics. Based on that, a Linear Quadratic Regulator (LQR) with feed forward is utilized to track the reference trajectories. In the feedback loop, this LQR controller minimizes the sum of tracking error and steering angle to optimize the tracking performance. The feed forward controller is used to compensate for the steady state error.

E. Drive-by-Wire System

We built a drive-by-wire system for Toyota electrical COMS vehicle. Three linear Maxon motors are used to control the steering wheel, throttle, and brake, respectively. The motor controllers communicates with the embedded motion PC by means of a CAN BUS channel which runs at 1MBit/s data rate. The status of the motors and the command and feedback data coming from/to the controllers are transferred all the time at 100Hz frequency during operation. This allows smooth operation of the Drive-By-Wire interface.

IV. EXPERIMENTS

We tested our solution on a Toyota electrical ECOMS vehicle with our self-built drive-by-wire system. Two SICK LMS151 2D laser scanners are mounted on the top and looking forward, as shown in 1b to detect the lane markers, road curbs and obstacles. A wheel encoder is mounted on the left rear wheel and a gyro mounted at the top center of rear wheels. A reliable and smooth path planning was implemented based on the piecewise lane fitting and prediction. LQR controller was also implemented w.r.t the CG of the vehicle.



(a) Autonomous driving in whole testing field.

(b) Part of the testing field during the sharp curve.

Fig. 6: Autonomous driving record. White line represents the lane markers, brown lines represent the road curbs, green line presents the lane prediction, blue line represents the real-time smooth path planning result, and the gray line represents the vehicle's odometry recorded.

Fig. 6 illustrates the autonomous driving data recorded. We can see that the vehicle's trajectory matches the path planned accurately, and at the sharp curves (round-about area), the trajectory is smoother than the planned path as shown in Fig. 6b.

Fig. 7 and 8 shows the input errors and output steering angle & velocity to/from LQR controller, respectively. The target velocity was set to 0 when obstacles are detected, and set to a lower speed during the sharp turning.

V. CONCLUSION

The road infrastructure detection and the V2I communication need further development for the future driverless car, as well as the HD maps to contain the V2I informations. Instead, this paper focus on the autonomous service vehicle to simplify the problem regardless of the issues of V2I and maps above. A unique map free lane following solution has been proposed for the autonomous service vehicle. An innovative laser configuration was proposed to take care of sharp curve lanes. The lane detection based on the 2D laser's raw data is fast and accurate. The path planning based on lane fitting and prediction is reliable and intuitive. And a self-built drive-by-wire system assured our testing and demonstration to be achieved and accurately.

Our future work includes: to transfer the drive-by-wire system to more vehicles; to implement a service vehicle for a specific function, such as a sweeper car; and a selectable GPS module for remote monitoring.

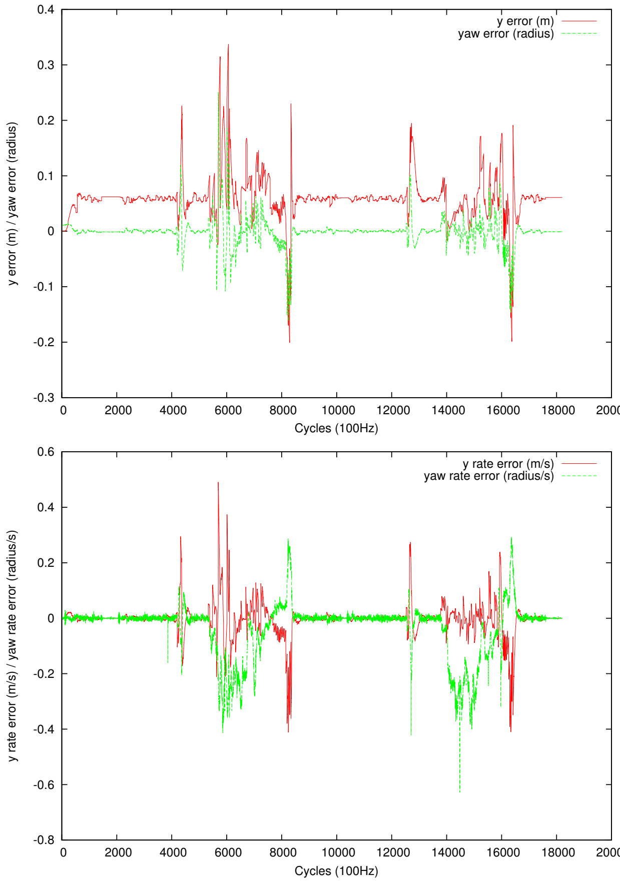


Fig. 7: Errors of $y, \dot{y}, \theta, \dot{\theta}$ between odometry and planned path for LQR controller.

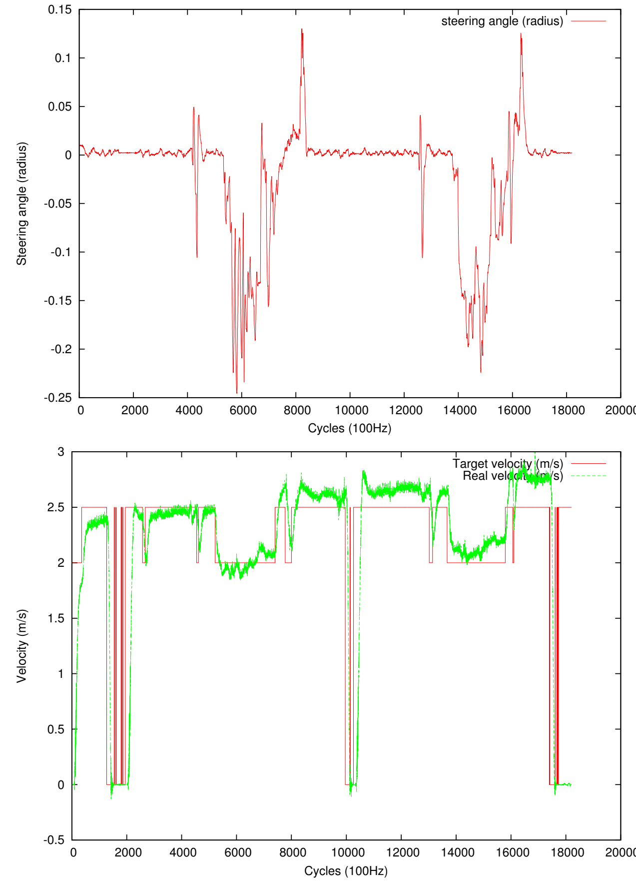


Fig. 8: The outputs of steering angle and target velocity from the LQR controller, and the real velocity from the vehicle.

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