A unified framework of the automated lane centering/changing control for motion smoothness adaptation

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Abstract — This paper describes an automated lane centering/changing control algorithm that was developed at General Motors Research and Development. Over the past few decades, there have been numerous studies in the autonomous vehicle motion control. These studies typically focused on improving the control accuracy of the autonomous driving vehicles. In addition to the control accuracy, driver/passenger comfort is also an important performance measure of the system. As an extension of authors’ prior study, this paper further considers vehicle motion control to provide driver/passenger comfort based on the adjustment of the lane change maneuvering time in various traffic situations. While defining the driver/passenger comfort level is a human factor study topic, this paper proposes a framework to integrate the motion smoothness into the existing lane centering/changing control problem. The proposed algorithm is capable of providing smooth and aggressive lane change maneuvers according to traffic situation and driver preference. Several simulation results as well as on-road vehicle test results confirm the effectiveness of the proposed algorithm.

I. INTRODUCTION

In recent years, the automotive industry has been highly active in developing commercially available autonomous driving features. Cruise control and adaptive cruise control are examples of such commercially available autonomous driving features, even though they provide only limited longitudinal control capability [1, 2]. Beyond such control functions, automated lateral motion control offers additional control capability in lateral motion. Lane keeping assist systems [3, 4] are already in production by some automakers. While several automotive companies and suppliers have demonstrated lane keeping control [3-5], the Lane Centering (LC) control is still a prototype function and has not been fully evaluated for production deployment. The LC feature maintains the vehicle in the center of the current lane and it operates indefinitely until driver disengages it or the LC is not feasible due to driving or other system conditions. The automated Lane Change (LX) control [6, 7] further broadens the scope of lateral motion control to the multi-lane motion control.

In this paper, we propose a new feature, Adaptive Lane Centering/Change (ALC) control. The ALC emphasizes driver interaction and adaptation with the existing LC control feature. The ALC has an algorithm to detect driver’s motion smoothness preference and adjust the motion control aggressiveness to meet the driver’s preference or to accommodate traffic situations. For example, some drivers prefer smooth and slow lane change maneuver while a quick lane change maneuver is needed in certain situation such as heavy traffic. The approach in this paper tackling the motion smoothness adaptation is to decouple the path generation from the motion control. The path is obtained as a 5th order polynomial equation. Applying the path continuity constraints, the 5th order equation can be solved with a unique solution. The obtained path guarantees the 2nd order geometric smoothness. A varying time horizon is inserted into the polynomial equation as a tuning parameter for the path smoothness adjustment. The time horizon varies according to the distance of the lane center from the vehicle center and driver’s preference. For example, the path is generated with longer time horizon if the lane centering is initiated with a large initial lane offset or driver prefers a slow lane change.

One forward lane detection camera and a three-degree inertial sensor are used for lane and vehicle motion sensing. An Electrical Power Steering (EPS) system is used for the steering actuation. The Model Predictive Control (MPC) is adopted for the vehicle’s lateral motion control. In this framework, the control input is optimized over a fixed control time horizon. The obtained steering control is executed at every time step. Typically, lane centering is an infinite time horizon control problem. To simplify the control problem, only a few-second time horizon is considered, repeatedly. This simplified MPC solves the fixed time horizon control problem at each time step and avoids heavy computation so that the algorithm is appropriate for real time processing.

The vehicle state estimation function predicts the vehicle’s future trajectory based on the vehicle motion measurements (yaw rate, acceleration, speed, steering angle). In the control stage, the motion controller compares the desired path with the predicted path for the selected time horizon, and finally generates the steering torque command at each time step. A rate limit and a saturation functions are added to this stage to adjust the steering aggressiveness.

The proposed ALC control functions are implemented in one framework so that multiple motion smoothness can be achieved within one control methodology. Lateral acceleration is one measure that indicates driver/passenger comfort level. Relaxation, either in the desired path or in the steering control command, will change the motion smoothness and the comfort level. This paper considers the relaxation in the desired path generation.

To show the effectiveness of the algorithm, several simulation tests and on-road vehicle tests were performed.
Transient and steady-state control responses are typical performance measures of the LC/LX system. The lateral acceleration during the maneuvers is assessed as a performance measure of the motion control smoothness.

II. SYSTEM CONFIGURATION

A monochrome vision camera is a typical sensor for the forward lane marker detection. Accelerometers and rate gyros are installed in the vehicle for the vehicle motion measurements. The EPS is the actuator for the steering maneuver. The lateral motion caused by the differential brakes and rear steer was not considered in the scope.

![Figure 1. Flow diagram of the lane centering/change algorithm](image)

Figure 1 shows a block diagram of the overall lane centering/change control algorithm. The forward vision system detects lane markings and represents the roadway in a third order polynomial equation. The roadway estimation module compensates the vision system time delay and predicts the future values of the roadway’s lateral offset \(y_r\), yaw angle \(\varphi_r\), roadway curvature \(\rho_r\), and the curvature derivative \(d_r\), with respect to the vehicle coordinate system.

Figure 2 shows the coordinate system adopted in this paper. The origin of the coordinate system is attached to the vehicle center with the \(x\)-axis along the vehicle forward direction and the \(y\)-axis toward the left. The vehicle yaw rate \(\dot{\varphi}_r\), the longitudinal speed \(v_x\), and the steering angle \(\delta\) are assumed to be measured. The vehicle lateral speed, \(v_y\), is typically not directly measurable by the automotive standard sensors. The measured yaw rate is combined with the steering angle measurement to estimate the vehicle lateral speed [8].

The vehicle’s future lateral position \(\hat{y}\) with respect to the current vehicle center is predicted using the vehicle dynamic states, \(r\) and \(v_y\). The driving adaptation module in Figure 1 is a new module added to the existing lateral control framework [6]. It detects driver’s motion smoothness preference, and adapts the path generation using a path smoothness parameter.

The lateral motion control algorithm compares the predicted roadway path, \((\hat{x}, \hat{y})\), with the vehicle’s desired path, \((x_d, y_d)\), and calculates a steering angle command \(\delta_{cmd}\) such that the path difference is minimized. The EPS system currently available in automotive production vehicles takes a steering torque as an overlay command. In this paper, the steering system is modeled as the 3rd order dynamic model, (1), with an \(n\)-step time delay, \(z^{-n}\). The parameters of the dynamic model, \((p_1, p_2, q_1, q_2, q_3, n)\), are found from the open loop tests using the least square methods.

\[
\frac{\delta}{\tau_{cmd}} = \frac{z^{-n}(p_1 + p_2 z^{-1})}{1 + q_1 z^{-1} + q_2 z^{-2} + q_3 z^{-3}}
\]

III. ROADWAY MODEL

In the prior study [6], the roadway is represented in a second order polynomial equation. However, it is often noted that rear world roads cannot be represented correctly with a single second order polynomial equation. In particular, a straight to curve or a curve to straight transition requires more than second order degree in the road representation. In this paper, we consider varying model orders. For example, a straight road can be represented as a first order model, a constant curvature road as a second order, and a transition section as a third order. Thus the following equation is used

\[
y_{lan}(x) = c_3 x^3 + c_2 x^2 + c_1 x + c_0
\]

where \(x\) is a distance along the vehicle longitudinal direction and \(y_{lane}\) is the lateral distance measured from the vehicle center to the lane center line along the left direction, \(c_2\) and \(c_3\) can be zero depending on road types.

IV. PATH PLANNING AND RELAXATION

We define \((x_d(t), y_d(t))\) as the desired vehicle position at time \(t\) with respect to the vehicle-centered coordinate system. Without loss of generality, we assume that the desired path generation begins at \(t=0\). Thus we can set the initial position and the initial orientation of the desired path at \(t=0\) as

\[
(x_d(0), y_d(0)) = (x(0), y(0)) = (0,0),
\]

\[
\frac{dy_d(0)}{dx_d} = \frac{dy(0)}{dx} = 0.
\]

The path planning algorithm begins with specifying a time \(t_{path}\) to complete a lane change or a lane centering maneuver (drive the vehicle to the lane center of the target lane from the current vehicle position). While human factor study would determine the most comfortable lane centering/change time of
This paper considers how this time is integrated smoothly into the existing control problem. Thus the control problem is solved in the same framework. For simplicity, we consider the lane centering problem as a subset of the lane changing problem and use the $t_{path}$ for both problems.

For real-time implementation, computing efficiency is another important design consideration in the path planning. The design goal of the path generation algorithm is to develop a fast computing algorithm, and generate a smooth path so that geometric continuity along the roadway is guaranteed up to second order at the beginning and the end of the planned path. This second order continuity condition at the initial position of the path is written as

$$\frac{d^2 y}{dx^2} \bigg|_{x=0} = \frac{d^2 y_{lane}}{dx^2} \bigg|_{x=0}$$

(4)

The continuity conditions at the end of the path are

$$\begin{aligned}
y_y(t_{peak}) &= y_{lane}(t_{path}) + L, \text{ for LX path plan} \\
y_y(t_{path}) &= y_{lane}(t_{path}), \text{ for LC path plan} \end{aligned}$$

(5)

$$\frac{dy_y}{dx} \bigg|_{x=t_{peak}} = \frac{dy_{lane}}{dx} \bigg|_{x=t_{peak}},$$

$$\frac{d^2 y_y}{dx^2} \bigg|_{x=t_{peak}} = \frac{d^2 y_{lane}}{dx^2} \bigg|_{x=t_{peak}},$$

where $L$ indicates the lane width. Considering these continuity conditions, we propose a fifth order polynomial equation for the desired path generation problem:

$$y_y(t) = a_1 x^3(t) + a_2 x^2(t) + a_3 x(t) + a_4 x(t) + a_5,$$  

(6)

The above equation can be rewritten in a form of the normalized model,

$$\begin{aligned}
y_y(t) &= a_{s,1} s_x^3(t) + a_{s,2} s_x^2(t) + a_{s,3} s_x(t) + a_{s,4} s_x(t) + a_{s,5} \\
x_y(t) &= \frac{x(t)}{(v_y \cdot \ell_{peak})} \\
y_y(t) &= \frac{y_y(t)}{L} \end{aligned}$$

(7)

Applying the roadway model (2) and the continuity conditions (3-5) into (7), the linear equation problem (7) can be solved as

$$\begin{bmatrix} a_{s,1} \\ a_{s,2} \\ a_{s,3} \\ a_{s,4} \\ a_{s,5} \end{bmatrix} = \frac{1}{L} \begin{bmatrix} 10 & 6 & 0 & 1 \\ -15 & -8 & 0 & 0 \\ 6 & 3 & 0 & 0 \end{bmatrix} \begin{bmatrix} c_0 \\ c_1 \cdot (v_y \cdot \ell_{peak}) \\ c_2 \cdot (v_y \cdot \ell_{peak})^2 \\ c_3 \cdot (v_y \cdot \ell_{peak})^3 \end{bmatrix}$$

(8)

Note that $c_0, c_1, c_2,$ and $c_3$ are the parameters representing the current roadway, and given by the forward-looking lane detection sensor. As explained, $t_{path}$ is the execution time of the path planning and is typically given by the human factor study. However, in this paper, $t_{path}$ is considered as a tuning parameter. By changing the $t_{path}$, the smoothness of the path is adjusted. For example, smaller value of $t_{path}$ generates more aggressive path.

The solution equation (8) is calculated every time step for a new desired path and it generates a path of second-order smoothness. For an additional aggressiveness adjustment, a new factor, $y_0$, is added into the path planning initial condition (3).

$$(x_y(0), y_y(0)) = (0, y_0),$$

(9)

$y_0$ is an intentional discontinuity in the zeroth order condition. It allows the desired path to begin with an offset from the vehicle center. Thus, it creates more aggressive path. Combining (9) into (8), we can get

$$\begin{bmatrix} a_{s,1} \\ a_{s,2} \\ a_{s,3} \end{bmatrix} = \frac{1}{L} \begin{bmatrix} 10 & 6 & 0 \\ -15 & -8 & 0 \\ 6 & 3 & 0 \end{bmatrix} \begin{bmatrix} c_0 \\ c_1 \cdot (v_y \cdot \ell_{peak}) \\ c_2 \cdot (v_y \cdot \ell_{peak})^2 \\ c_3 \cdot (v_y \cdot \ell_{peak})^3 \end{bmatrix} + \begin{bmatrix} 1 - y_y/L \\ 0 \\ 0 \end{bmatrix}.$$  

(10)

Note that the solution of the path generation is in a closed form and the matrix in (10) is a constant matrix regardless of the road geometry and vehicle states. Therefore, the solution of the equation can be obtained by a few simple algebraic computations using the road geometry measurements. Once the solution is calculated, Equation (7) represents the desired path to complete the current lane change/lane centering maneuver.

Upon generating the desired path, the control algorithm calculates a future steering torque command to drive the vehicle to the desired path. Passenger’s comfort during the lane change maneuvering is one important design objective. Lateral acceleration is commonly used to represent passenger’s comfort. Given the current vehicle speed, $v_y$, the future lateral acceleration $a_y$ can be determined by the vehicle yaw rate, $r$, and the steering angle command $\delta_{cmd}$,

$$\begin{aligned}
\dot{v}_y(t) &= -\frac{C_y + C_{yf}}{m \cdot v_y} r(t) + \frac{b \cdot C_y - a \cdot C_{yf} + v_y}{m \cdot v_y} r(t) + \frac{C_y}{m} \delta_{cmd}(t) \\
a_y &= v_y \cdot r(t) + \dot{v}_y(t) \end{aligned}$$

(11)

where $C_y$ and $C_{yf}$ are the cornering stiffness of the front wheels and the rear wheels, $a$ and $b$ are the distances from the center of gravity of the vehicle to the front and rear axles, respectively, and $m$ is the vehicle total mass.

A human factors study recommends a certain limit, $a_y_{LIMIT}$, in the lateral acceleration not to exceed for driving comfort. To avoid the excessive lateral acceleration during the lateral motion control of LC/LX maneuver, a path relaxation method is applied to the desired path algorithm above. If the calculated steering command is expected to cause an excessive lateral acceleration, i.e., $|a_y| > a_y_{LIMIT}$, a new path is calculated with an extension in the path generation time, $t_{path} + \Delta t_{path}$, or with a reduced vehicle speed. In this paper, the time extension of the path is tried out first if $|a_y| >$
\(a_{y, \text{LIMIT}}\) can be avoided without a speed reduction. However, if the road itself is a tight curved road, i.e., the curvature of the upcoming road, \(\rho_{\text{road}}\), is
\[
\rho_{\text{road}} > \frac{a_{y, \text{LIMIT}}}{\nu_{x}^{2}} = \rho_{\text{LIMIT}}.
\] (12)
then it is not possible to achieve \(|a_{y}| < a_{y, \text{LIMIT}}\) given the current vehicle speed. In this situation, the LC/LX controller reduces the current vehicle speed until the expected lateral acceleration becomes less than \(a_{y, \text{LIMIT}}\). The road curvature is approximated into \(\rho_{\text{road}} \approx 6c_{3}x + 2c_{2}\), where \(c_{3}\) and \(d_{c2}\) are the forward camera measurements in (2). Thus a simple check of \(6c_{3}x + 2c_{2} > \rho_{\text{LIMIT}}\), will indicate whether a speed reduction is needed. If \(6c_{3}x + 2c_{2} \leq \rho_{\text{LIMIT}}\) is satisfied, the \(a_{y} < a_{y, \text{LIMIT}}\) can be achieved by the path generation time extension.

To find out the desired path (6) that meets the \(|a_{y}| < a_{y, \text{LIMIT}}\), we use the approximation of \(\rho_{\text{road}} \approx d^{2}y_{a} / dx^{2}\). Then a \(\Delta t_{\text{path}}\) can be found from the following equation
\[
\frac{d^{2}y_{a}}{dx^{2}} \cdot \frac{L}{v_{x} \cdot (t_{\text{path}} + \Delta t_{\text{path}})} < \rho_{\text{LIMIT}}.
\] (13)
The desired path of (7) with \(t_{\text{path}} + \Delta t_{\text{path}}\) into the solution (10) will generate a smooth path which does not exceed the lateral acceleration limit of \(a_{y, \text{LIMIT}}\).

In addition to the \(a_{y, \text{LIMIT}}\) check, it is often needed to change smoothness of the path for more comfortable or more aggressive LC/LX maneuver. \(\Delta t_{\text{path}}\) can be increased or decreased for this objectives. For example, quicker lane change maneuver is needed in heavy traffic situations. In this case, \(\Delta t_{\text{path}}\) can be negative value and added to the default \(t_{\text{path}}\) value. The human factor study can play with the \(\Delta t_{\text{path}}\) to find passengers‘ most comfortable LC/LX maneuver. In this case, \(\Delta t_{\text{path}}\) is served as a system tuning parameter. For a particular driver, \(\Delta t_{\text{path}}\) can be found during a manual lane change. When the driver makes a manual lane change, driver’s steering aggressiveness preference can be represented as the lane change execution time, \(t_{\text{path}} + \Delta t_{\text{path}}\). The deviation, \(\Delta t_{\text{path}}\), of the manual lane changes is measured and averaged in the driving adaptation module of Figure 1, and used for the automated LC/LX path generation.

V. TRAJECTORY CONTROL

The objective of the lateral control module in Figure 1 is to minimize the lateral position and the heading angle differences between the desired path profile and the predicted vehicle path over a finite time horizon, \([0, t_{\text{path}}]\). The steering angle command is the main control output of the controller. The desired vehicle speed can be adjusted according to the vehicle lateral acceleration check, \(a_{y} < a_{y, \text{LIMIT}}\). The lateral control objective is formulated as minimizing the following cost function:
\[
J = \sum_{i=0}^{N-1} \left( \mathbf{z}^{T} Q \mathbf{z} + \mathbf{Qd}^{T} \mathbf{Qd} + \mathbf{Rd}^{T} \mathbf{Rd} \right)_{i}
\] (14)
where \(N = t_{\text{path}} / t_{\text{s}}\), \(\hat{z} = z_{d} - \hat{z}\), \(z_{d} = [\nu_{d} \ \varphi_{d}]^{T}\), \(\hat{z} = [\dot{\nu} \ \dot{\varphi}]^{T}\), and \(k\) corresponds to the present time step. \(Q\) and \(R\) are tuning parameters. The model predictive control technique is used in the steering control law derivation. The detailed control law derivation can be found in [6].

VI. VEHICLE EXPERIMENTS

For verification of the algorithm effectiveness, several simulation tests and on-road vehicle tests were performed. A test vehicle was built for the LC/LX maneuver. This vehicle is equipped with a forward looking camera for lane marking detection, a rate gyro for the yaw rate sensing, a speed meter, steering angle sensor, and an EPS for steering actuation. Using this test vehicle, several vehicle tests are carried out to evaluate the proposed LC/LX algorithm.

Figure 3 and Figure 4 show the control results of two different lane changing operations on a straight road with \(t_{\text{path}} = 6\) sec, and 7.5 sec. The lane change time is measured from the time that the lane change starts to the time that the vehicle passes the target lane center. As shown in the figures, the actual lane change execution times are 5.8 sec and 7.5 sec, respectively. Due to road conditions, sensing inaccuracy, and system delay, 5.7 sec to 6.5 sec were observed for the \(t_{\text{path}} = 6\) sec lane change, and 7.4 sec to 8.3 sec for the \(t_{\text{path}} = 7.5\) sec lane change.
attempted without the path relaxation and it exceeds 0.15g limit.

Next scenario simulates a quick lane change maneuver assuming a heavy traffic situation, $\Delta t_{\text{path}} = -3$ sec (total of 3 sec lane change path) path is created for the quick lane change. As expected the lateral acceleration is increased up to 0.4g at the peak.

Figure 5. Lane change to the inner lane without a path relaxation (CarSim simulation)

Figure 6. Lateral acceleration during the lane change maneuver without a path relaxation (CarSim simulation)

Figure 7 and Figure 8 show the effectiveness of the path relaxation. A lane change in the same scenario with the path relaxation is performed. As shown in Figure 7, a new path is generated with $\Delta t_{\text{path}} = 1.5$ sec (total of 7.5 sec lane change path). The lateral acceleration is kept under 0.15g (Figure 8).

Figure 7. Lane change to the inner lane with a path relaxation (CarSim simulation)

Figure 8. Lateral acceleration during the lane change maneuver with a path relaxation (CarSim simulation)

VII. CONCLUSIONS

This study was motivated by human factors consideration of the effects of lateral motion control on driver/passenger comfort. As a study tool, the paper presented a control method and a path generation algorithm for the automated lane centering and changing control system. In addition to the authors’ prior study [6], the relaxation algorithm was added to the desired path generation. A flexible lateral control algorithm was proposed so the lane centering and lane change can be performed with different levels of motion smoothness. Using the relaxation algorithm, the path can be regenerated for smoother or more aggressive lateral motion control. This relaxation algorithm is added into the existing LC/LX algorithm within a unified framework, where the same lateral control algorithm was used without modification. A driving adaptation algorithm was also added to the upper layer of the desired path generation with an interface parameter between the adaptation algorithm and the desired path generation algorithm. The motion smoothness can be easily changed by adjusting this parameter. Several simulation tests and vehicle tests showed that the proposed algorithm effectively changes the motion smoothness is appropriate for automated lane centering and changing maneuver.

REFERENCES


