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CONTROL AND VALIDATION OF AUTOMATED LANE CENTERING AND LANE CHANGING MANEUVER

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ABSTRACT

This paper describes an automated lane changing control system that has been developed at General Motors Research and Development. This system uses a single monochrome camera to recognize lane markings on the road ahead and uses multiple short range radars to detect surrounding traffic and objects. A sensing unit calculates the host vehicle's lateral displacement and the heading angle from the center of its lane as well as the relative distance and relative speed of each object. Since the smoothness and comfort of lane change maneuvering are important measures of the control performance, the vehicle dynamic model is integrated into the desired path generation and vehicle's controller design to reduce the vehicle lateral acceleration and the lateral offset overshoot during the lane change maneuvering. To avoid heavy computation, a simplified model predictive control algorithm is proposed. The control algorithm calculates a steering angle command at the current time step to drive the vehicle to the desired path. The control method and algorithms are implemented on a demonstration vehicle and validated at straight roads and various curve roads of up to 0.001 [1/m] curvature for different vehicle speeds up to 100 [km/hr]. The results show that lane change maneuvering is successfully completed with lateral offset error less than 20 cm.

INTRODUCTION

The automotive industry has made considerable effort to enhance driving safety and convenience over past decades. One of the new areas of interest in the driving convenience is autonomous and semi-autonomous driving. Cruise control is one example of semi-autonomous driving functions. Adaptive Cruise Control [1, 2] has advanced the conventional cruise control system by automatic adjustment of the host vehicle speed and maintaining a constant headway with the vehicle in front. Further enhancements are achieved by Smart Adaptive Cruise Control (SACC) [3], which controls the vehicle speed according to the road curvature and the road speed limit as well as the traffic conditions.

Beyond the longitudinal control in autonomous fashion, there are increasing research and development for autonomous lateral motion control in academia and industry. Lane keeping assist [4, 5] and Lane departure warning [6, 7] systems are already in production by some automakers, and automated lane keeping control systems [4, 5, 8] are actively developed in automotive industry. The automated lane change control further broadens the scope of lateral motion control, which includes sensing of surrounding traffic and objects, collision threat assessment, adaptive cruise control, and driver interaction, as well as the vehicle lateral motion control. In this paper, we have focused on the vehicle's motion control for a smooth lane changing maneuver in autonomous fashion. The lane change maneuvering is a typical finite horizon control problem. We have adopted the Model Predictive Control (MPC) where the control input is optimized over the time horizon considered, and the optimal value obtained for the current time step is actually implemented. A simplified MPC algorithm is proposed to avoid heavy computation so that the algorithm is appropriate for real time processing. In addition, we have considered a unified framework for lateral motion control so that the lane changing and lane centering functions are performed within one control methodology. When the lateral controller is designed, the longitudinal motion control is usually considered in the same framework since the lateral dynamics of vehicle is affected by the vehicle's longitudinal speed. An approach adopted in this paper is to tackle the vehicle motion control problem with decoupled control tasks, simultaneously. In particular, 1) the vehicle's longitudinal speed is adjusted by adaptive cruise control function that maintains the driver's requested set speed and headway, and 2) given the vehicle speed, the lateral motion controller performs lane change and lane centering maneuvering to drive the vehicle on the desired path profile.

The lane changing controller consists of path planning, vehicle state estimation, and motion control algorithm. The path planning function produces an achievable desired path in the form of the host vehicle's lateral displacement and the heading angle from the center of its lane. Using vehicle's dynamic model, the vehicle state estimation function predicts the vehicle's future trajectory based on the current vehicle states. The motion controller compares them with the desired path at multiple look-ahead points, and finally, the controller generates the steering angle command at each time step. The control algorithm is designed using a finite horizon optimal control scheme with simplification so that the control command tracks the future desired set points over the prescribed time horizon. Relaxation of the desired path and the control output is necessary to avoid excessive lateral acceleration which results in driver and passenger discomfort. If high excessive lateral acceleration during a lane change control is predicted, particularly in high curvature roads, the controller reduces the vehicle speed until the lateral acceleration during the lane change maneuvering falls under the limit.

In the upcoming sections, we present the proposed control method and algorithms, which is implemented on a demonstration vehicle and discuss the results based on the vehicle test results.

SYSTEM OVERVIEW

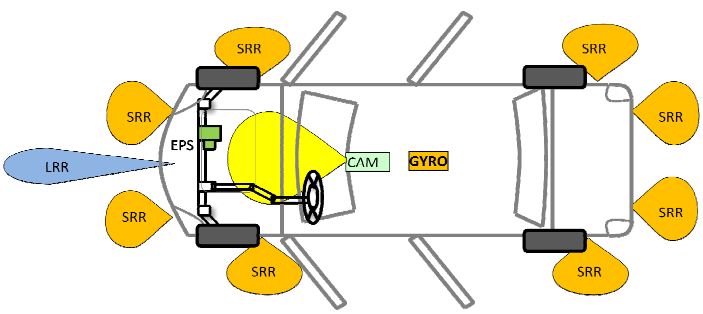

FIGURE 1 CONCEPTUAL DIAGRAM OF SYSTEM CONFIGURATION

Figure 1 shows the sensor and the actuator configurations used in the test vehicle. A monochrome vision camera is used for forward lane marker detection and a long-range radar detects objects in front of the vehicle. Two additional short-range radars are installed in the front to cover the region that the long-range radar does not see. Six additional short-range radars are added in sides and rear to monitor traffic and objects coming from those directions. Since the relative lateral motion to objects are small compared to the longitudinal motion when the vehicle is moving forward, 40m range with 60 deg of viewing angle radars would suffice the purpose of operation. A rate gyro is installed to measure the vehicle's yaw rate. The measured yaw rate is combined with steering angle measurements to estimate the vehicle states including lateral speed.

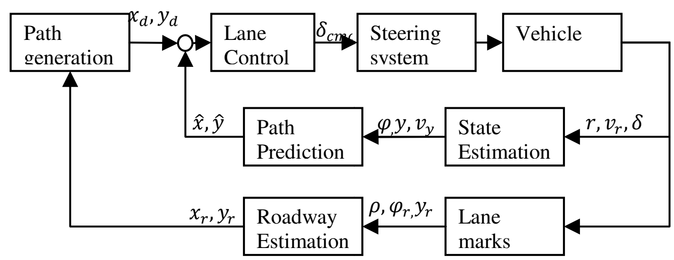

FIGURE 2 FLOW OF LANE CHANGE CONTROL

Figure 2 shows a block diagram of the overall lane change control algorithm. The forward vision system detects lane markings and recognizes the roadway information with the lateral offset y_r, roadway curvature ρ, and yaw angle φ_r of the the roadway with respect to the vehicle coordinate system. The roadway lateral position y_r can be further predicted using the vehicle dynamics as a function of vehicle longitudinal position x_r. The lateral motion control algorithm compares the predicted predicted roadway path with the vehicle's desired path, (x_d, y_d), and calculates a steering angle command δ_{cmd} by minimizing the path difference. The vehicle steering system has an internal control loop to control the vehicle steering angle as commanded. The vehicle yaw rate r, the longitudinal speed v_x, and the steering angle δ are assumed to be measured, and the lateral speed v_y, the yaw angle φ, and the lateral position $\hat{y}$ are are predicted over time as function of the vehicle longitudinal position $\hat{x}$.

VEHICLE LATERAL DYNAMICS AND ROADWAY LOOK-AHEAD MODEL

A typical bicycle model is depicted in Figure 3 with the coordinate system (x, y), attached to the center of vehicle. a and b are the distances from the center of gravity of the vehicle to the front and rear axles, respectively. Using the above variables, the vehicle dynamics equation can be represented by:

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}_c \cdot \mathbf{x} + \mathbf{B}_c \cdot \mathbf{u} \\ \mathbf{z} &= \mathbf{C}_c \cdot \mathbf{x} \end{aligned} \qquad (1)$$

with $\mathbf{x} = [y \quad \varphi \quad v_y \quad r]^T$, $\mathbf{u} = \delta$, $\mathbf{B_c} = \begin{bmatrix} 0 & 0 & \frac{C_f}{m} & \frac{aC_f}{I} \end{bmatrix}^T$,

$\mathbf{C_c} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$, and

$$\mathbf{A_c} = \begin{bmatrix} 0 & v_x & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\frac{C_f + C_r}{mv_x} & \frac{bC_r - aC_f}{mv_x} - v_x \\ 0 & 0 & \frac{bC_r - aC_f}{I_z v_x} & -\frac{a^2 C_f + b^2 C_r}{I_z v_x} \end{bmatrix},$$

where C_f and C_r are the cornering stiffness of front wheels and and rear wheels, respectively, m is the vehicle total mass, and $I_z$is the moment of inertia around the center of mass perpendicular to the plane where the vehicle is located.

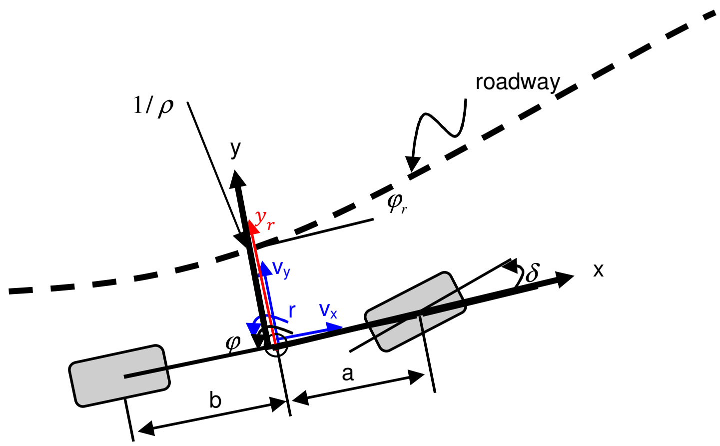

FIGURE 3 LATERAL DYNAMIC MODEL

Lane markings are recognized by the forward vision camera and represented with the curvature ρ, the yaw angle of the lane marking φ_r, and the lateral offset y_r to the center of the the current lane with respect to the vehicle coordinate system. In high speed maneuvering, the detection range of the camera system is not long enough to cover the distance of roadway needed for one complete lane change. Thus, we provide a roadway look-ahead model integrated with the vehicle lateral dynamics to predict the roadway beyond the sensing range.

$$\begin{aligned} \dot{\mathbf{x}}_r &= \mathbf{A}_r \mathbf{x}_r + \mathbf{B}_r \mathbf{u} + \mathbf{G}_r \rho \\ \mathbf{z}_r &= \mathbf{C}_r \mathbf{x}_r \end{aligned}, \qquad (2)$$

with $\mathbf{x}_r = [y_r \quad \varphi_r \quad v_y \quad r]^T$, $\mathbf{B}_r = \mathbf{B}$, $\mathbf{C}_r = \mathbf{C}_c$, $\mathbf{G}_r = [0 \quad v_x \quad 0 \quad 0]^T$, and

$$\mathbf{A}_r = \begin{bmatrix} 0 & v_x & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -\frac{C_f + C_r}{mv_x} & \frac{bC_r - aC_f}{mv_x} - v_x \\ 0 & 0 & \frac{bC_r - aC_f}{Iv_x} & -\frac{a^2 C_f + b^2 C_r}{Iv_x} \end{bmatrix}.$$

PATH PLANNING AND RELAXATION

The path planning algorithm begins with specifying a time t_{LX} to complete a lane change maneuvering. The t_{LX} is initially initially pre-specified by the vehicle design concept. For example, a sporty style vehicle has a tendency of quicker lane change maneuvering than a comfort style vehicle. In addition, we assume that the desired path generation begins at t=0 and define $(x_d(t), y_d(t))$ as the desired vehicle position at time t with respect to the vehicle coordinate system. Then, without loss of generality, we can set the initial position and the initial orientation of the desired path at t=0,

$$(x_d(0), y_d(0)) = (x(0), y(0)) = (0,0), \qquad (3)$$

$$dy_d(0)/dx_d = dy(0)/dx = 0.$$

Smooth maneuvering is one important measure of the lane changing control performance, while the computing efficiency is a design consideration for real-time implementation. The design goal of the path generation algorithm is to develop a fast computing algorithm, and the algorithm generates a smooth path so that geometric continuity, up to second order, with the roadway is guaranteed at the beginning and the end of lane change maneuvering. The continuity conditions are written as

$$\begin{aligned} \left.\frac{d^2 y_d}{dx_d^2}\right|_{t=0} &= \left.\frac{d^2 y_r}{dx^2}\right|_{t=0} \\ y_d(t_{LX}) &= y_r(t_{LX}) + L, \\ \left.\frac{dy_d}{dx_d}\right|_{t=t_{LX}} &= \left.\frac{dy_r}{dx}\right|_{t=t_{LX}}, \\ \left.\frac{d^2 y_d}{dx_d^2}\right|_{t=t_{LX}} &= \left.\frac{d^2 y_r}{dx^2}\right|_{t=t_{LX}}, \end{aligned} \qquad (4)$$

where L indicates the lane width, and $y_r(t_{LX})$ is the predicted lateral distance to the center of the current lane at time t_{LX}. $y_r(t)$ is estimated using the roadway look-ahead model in Equation (2). Note that L and $y_r(t)$ follow the vehicle coordinate system shown in Figure 3. Thus, for example, L will be a positive value at a left lane change execution and a negative value at a right lane change.

With these considerations, we propose a fifth order polynomial equation for the desired path generation problem:

$$y_n(t) = a_{n,5}x_n{}^5(t) + a_{n,4}x_n{}^4(t) + a_{n,3}x_n{}^3(t) + a_{n,2}x_n{}^2(t) + a_{n,1}x_n(t) + a_{n,0} \tag{5}$$

with,

$$x_n(t) = \frac{x_d(t)}{x_d(t_{LX})}$$
$$y_n(t) = \frac{y_d(t)}{y_d(t_{LX})} \tag{6}$$

Applying the continuity conditions (3) and (4) into (5), the linear equation problem (5) can be solved as

$$a_{n,0} = a_{n,1} = 0, a_{n,2} = 0.5\frac{d^2 y_r(0)}{dx^2}\cdot\frac{x^2(t_{LX})}{y_r(t_{LX})}$$
$$\begin{bmatrix} a_{n,3} \\ a_{n,4} \\ a_{n,5} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 3 & 4 & 5 \\ 6 & 12 & 20 \end{bmatrix}^{-1} \begin{bmatrix} \dfrac{y_r(t_{LX})}{x(t_{LX})} - 0.5\dfrac{d^2 y_r(0)}{dx^2}\cdot x(t_{LX}) \\ \dfrac{dy_r(t_{LX})}{dx}\cdot - \dfrac{d^2 y_r(0)}{dx^2}\cdot x(t_{LX}) \\ \dfrac{d^2 y_r(t_{LX})}{dx^2}\cdot x(t_{LX}) - \dfrac{d^2 y_r(0)}{dx^2}\cdot x(t_{LX}) \end{bmatrix} \cdot \frac{x(t_{LX})}{y_r(t_{LX})}. \tag{7}$$

Note that the solution of the path generation is in closed form and the matrix in (7) 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 condition. Once the solution is calculated, Equation (5) represents the desired path to complete the current lane change maneuvering.

Upon generating the desired path, the control algorithm calculates a future steering angle command to drive the vehicle to the path. Passenger's comfort during the lane change maneuvering is one important design objective. Lateral acceleration is commonly used to represent passenger's comfort. From lateral dynamics model (1), the lateral acceleration a_y can be estimated by yaw rate measurement and steering angle command δ_{cmd},

$$\dot{v}_y(t) = -\frac{C_f + C_r}{m\cdot v_x}\cdot v_y(t) + \left(\frac{b\cdot C_r - a\cdot C_f}{m\cdot v_x} - v_x\right)\cdot r(t) + \frac{C_f}{m}\cdot\delta_{cmd}(t)$$
$$a_y = v_x\cdot r(t) + \dot{v}_y(t) \tag{8}$$

To avoid excessive lateral acceleration during the lane change maneuvering, a path relaxation method is applied to the desired path calculated above. If the calculated steering angle 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 lane change completion time, $t_{LX} + \Delta t_{LX}$. The path is iteratively calculated until the expected lateral acceleration falls under the limit. In a high curvature road, we further need to reduce the vehicle speed to keep the lateral acceleration within the limit, $\dot{v}_y < a_{y,LIMIT}$. For example, if the calculated lane change completion time reaches to a certain time limit, $t_{LX} + \Delta t_{LX} = t_{LX,LIMIT}$, and the lateral acceleration exceeds the limit, the lane change controller reduces the current vehicle speed. The cruise control unit usually has a predefined acceleration and deceleration profile. So the lane change controller reduces the vehicle speed along the predefined deceleration profile until the expected lateral acceleration becomes less than $a_{y,LIMIT}$.

CONTROL ALGORITHM

The objective of the lane change maneuvering control is to minimize the lateral displacement and the vehicle heading angle differences between the desired path profile and the predicted vehicle path over a finite time horizon, $[0, t_{LX}]$. Steering angle command is the main control output and the desired vehicle speed can be adjusted depending on the vehicle lateral acceleration.

Recall the vehicle dynamic model (1) and the vehicle states of interest,

$$\mathbf{z}(k) = \begin{bmatrix} y & \varphi \end{bmatrix}^T. \tag{9}$$

The discretized equation of the vehicle dynamic model (1) with sampling time, t_s, can be written as

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}\mathbf{u}(k)$$
$$\mathbf{z}(k) = \mathbf{C}\mathbf{x}(k) \tag{10}$$

where $\mathbf{x} = \begin{bmatrix} y & \varphi & v_y & r \end{bmatrix}^T$, $\mathbf{u} = \delta$, $\mathbf{A} = e^{\mathbf{A}_c t_s}$, $\mathbf{B} = \int_0^{t_s} e^{\mathbf{A}_c\alpha}\mathbf{B}_c d\alpha$, and $\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$.

Note that the road geometry information is captured only by the desired path generation. The controller design would not explicitly use the road information. The main task of the controller is to minimize the difference of the desired path and the predicted path. Consider the difference of the paths at time step k

$$\tilde{\mathbf{z}}(k) \equiv \mathbf{z}_{\mathbf{d}}(k) - \mathbf{z}(k), \tag{11}$$

where $\mathbf{z_d}(k) = [y_d \quad \varphi_d]^T$ is the desired states of the vehicle.

Now, we formulate the control objective as minimizing the following cost function:

$$J = \sum_{i=0}^{N-1} [\tilde{\mathbf{z}}^T(k+i+1)\mathbf{Q}(k+i+1)\tilde{\mathbf{z}}(k+i+1) + u(k+i)R(k+i)u(k+i)] \qquad (12)$$

where $N = t_{LX}/t_s$, $\tilde{\mathbf{z}}(k) = \hat{\mathbf{z}}(k) - \mathbf{z}_d(k)$, $\mathbf{Q}(k+i+1) \geq 0$, $R(k+i) > 0$, and k corresponds to the present time step. In the model predictive control the control input u is optimized over the whole time horizon considered, but only the optimal value obtained for the current time step is actually implemented. Then the system is allowed to evolve one sample, new measurements are collected and the optimization process is repeated. In light of the model predictive control implementation, we propose one simplification in this paper. In the controller design we consider the control input only at the current time step, thus we are looking for the optimal control input u at the current time step without the future control input consideration, i.e.,

$$u(k+i) = 0, i > 0. \qquad (13)$$

The control algorithm begins with specifying a lane change completion time t_{LX}. As the lane change maneuvering moves along, the time left to complete the current lane change goes down to 0. The amount of the reduced time horizon is replaced with the same amount of time for lane centering, thus the length of the control horizon is fixed throughout a lane change control unless an excessive lateral acceleration is estimated. By applying the conventional optimization method to the cost function (12) subject to the vehicle dynamic Equation (10), the optimal control input at time step k can be obtained as

$$u(k) = \frac{\sum_{i=0}^{N-1} \left(\mathbf{z_d}(k+i+1) - \mathbf{CA^{i+1}x}(k)\right)^T Q(k+i+1)(\mathbf{CA^iB})}{\sum_{i=0}^{N-1} (\mathbf{CA^iB})^T Q(k+i+1)(\mathbf{CA^iB}) + R(k)} \qquad (14)$$

Denominator term of (14) indicates the effect of the control input for the next N time horizons and the numerator term is the summation of the path differences between the desired path and the predicted path. Note that the denominator of (14) is a scalar and non-zero positive value since $R(k+i) > 0$, so a unique solution exists.

VEHICLE EXPERIMENTS

Actual vehicle tests are carried out to evaluate the proposed lane changing control algorithm. Figure 4 and Figure 7 illustrate the control results of lane centering and lane changing operation on a straight road and a curved road of 1100 m radius, respectively. The operation states in Figure 4 and Figure 7 indicate the current control mode. The low level of the state indicates that the vehicle is under lane centering control and the high level of the state indicates lane changing control. The up-arrow indicates lane change control initiation. The lateral offset was measured by the forward vision camera and fed back to the controller. Figure 4 shows five sets of lane change operations and Figure 7 shows six sets of lane change operation with the lane change completion time of 5 sec, initially. For the path relaxation, the lateral acceleration is programmed to be limited by 0.2 m/s^2. As seen in Figure 7, the lane change maneuvering into the inner lane at the curved road takes longer than the lane change to the outer lane (see time differences of the operation state of first, third, and fifth lane change vs. second, fourth, and sixth lane change in Figure 7). Figure 5 and Figure 8 show the steering angle command and measurement throughout the lane changing control maneuvering. Figure 6 and Figure 9 show the lateral acceleration and the vehicle speed. The test was performed with the vehicle speed varying between 8.0m/s to 12.0m/s (see Figure 6) and 17.5m/s to 19.5m/s (see Figure 9). As seen in the test results, the proposed algorithm performs the lane changing control within 20cm lateral displacement accuracy and 5sec completion time with the speed and the curvature variations of the roadway.

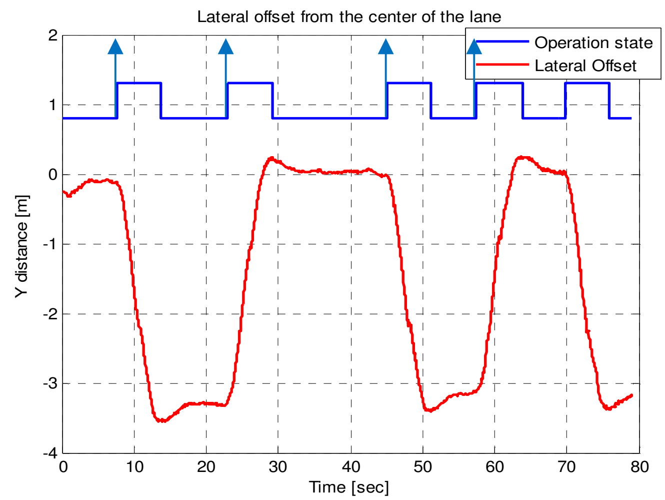

FIGURE 4 LATERAL DISPLACEMENT MEASURED FROM THE CENTER OF THE VEHICLE TO THE CENTER OF CURRENT LANE DURING LANE CENTERING AND LANE CHANGING CONTROL ON A STRAIGHT ROAD. THE UP-ARROWS INDICATE THE INITIATION OF LANE CHANGE MANEUVERING.

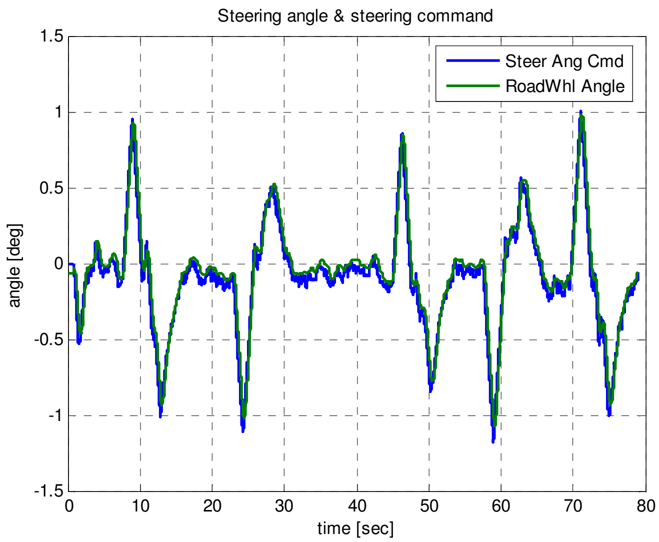

FIGURE 5 STEERING ANGLE MEASUREMENT AND STEERING COMMAND DURING LANE CHANGE CONTROL ON A STRAIGHT ROAD

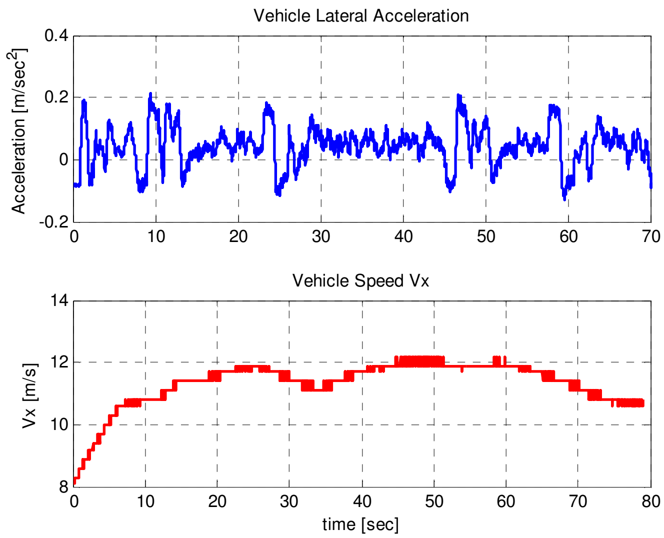

FIGURE 6 ESTIMATED VEHICLE LATERAL ACCELERATION AND VEHICLE SPEED MEASUREMENT DURING LANE CHANGE MANEUVERING ON A STRAIGHT ROAD

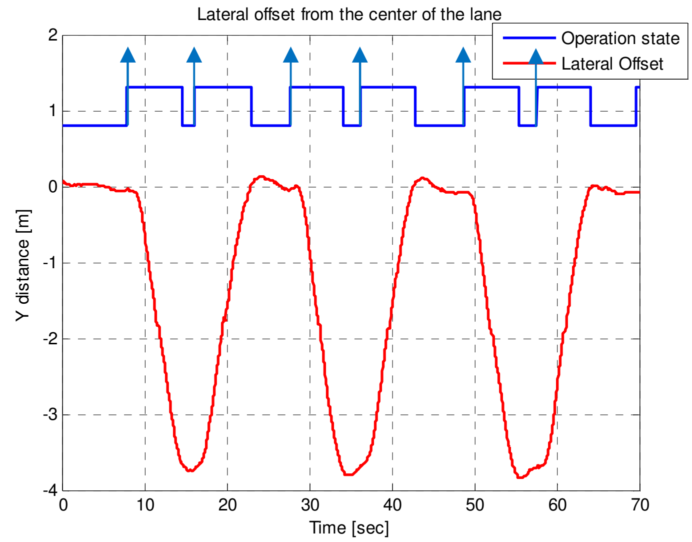

FIGURE 7 LATERAL DISPLACEMENT MEASURED FROM THE CENTER OF THE VEHICLE TO THE CENTER OF CURRENT LANE DURING LANE CENTERING AND LANE CHANGING CONTROL ON A CURVED ROAD. THE UP-ARROWS INDICATE THE INITIATION OF LANE CHANGE MANEUVERING.

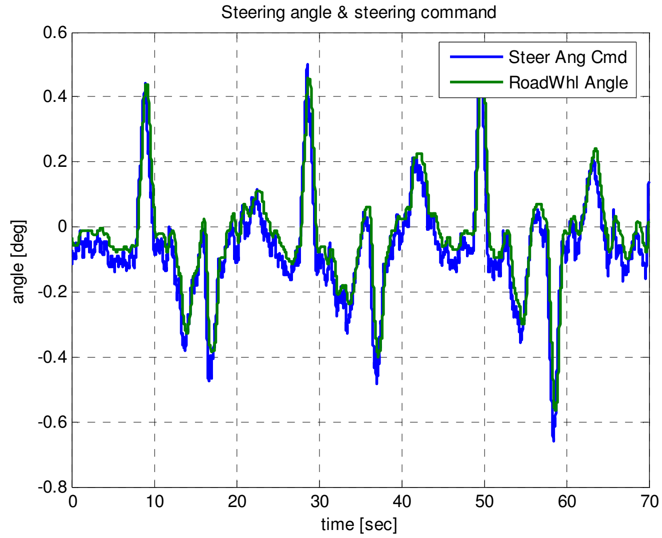

FIGURE 8 STEERING ANGLE MEASUREMENT AND STEERING COMMAND DURING LANE CHANGE CONTROL ON A CURVED ROAD

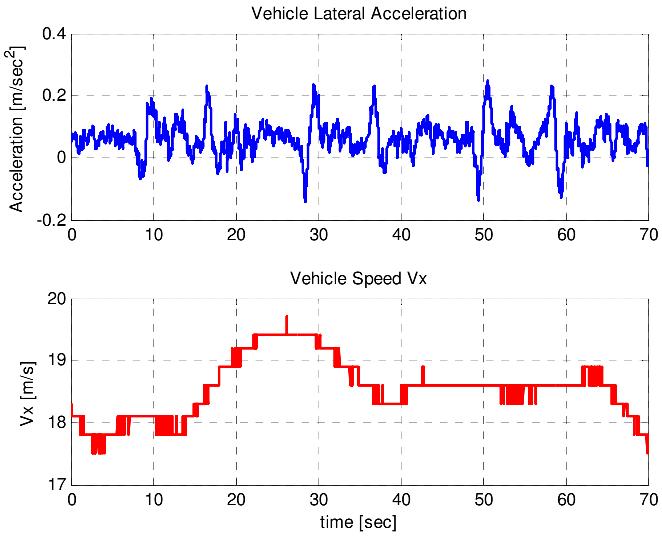

FIGURE 9 ESTIMATED VEHICLE LATERAL ACCELERATION ESTIMATED AND VEHICLE SPEED MEASUREMENT DURING LANE CHANGE MANEUVERING ON A CURVED ROAD

CONCLUSION

This paper presented a control method and a path generation algorithm for an automated lane changing control system. A single forward vision camera is used to recognize lane markings and multiple radars are used to detect surrounding traffic and objects that may cause a collision during the lane changing maneuvering. A simplified model predictive control method is developed for the real time computation efficiency. The control system proposed in this paper was implemented on a vehicle with the required steering system modification and necessary sensors installed. The proposed algorithm was tested at straight roads and various curved roads. The test results show that the proposed architecture and control design is appropriate for automated lane changing maneuver on straight and curved highways with no more than 0.001 [1/m] curvatures for the vehicle speeds of up to 110 km/h.

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