DIRECT TRAJECTORY OPTIMIZATION OF VEHICLE EVASIVE MANEUVERS

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Abstract—Many steering control systems have been developed to reduce road departures by performing lane change or evasive maneuvers. In most of these systems a controller was designed to make the vehicle follow a desired trajectory. In this research, finding desired trajectory based on some defined design criteria will be studied by directly optimizing the trajectory. This will be done by developing a model of the vehicle and using optimization techniques. The results will be compared to the trajectories suggested by other researchers. Based on the results, a new system with preferred trajectory will be developed to assist the driver in performing lane change or evasive maneuver in straight and curved lanes.

To test ability of the controller to accommodate disturbances and nonlinearities of the real vehicle, the developed controller will be implemented on a complex model of a car in a commercial software package and the results will be compared to the simulation results.

I. INTRODUCTION

Studies on Fatal Analysis Reporting System (FARS) showed that run-off road crashes were responsible for 34% of total fatalities in 2008; while including all types of road departure crashes, these kinds of crashes were responsible for about 53 percent of all road fatalities [1]. Lane departure warning systems have been developed to reduce lane departures. However, some systems have been developed to have more control on the car, and their task is to keep the vehicle in the lane. Vehicle steering control to perform evasive maneuvers or lane change maneuvers has been studied by various researchers using linear and nonlinear control systems [2-7]. Most of these studies used predefined desired trajectories as the optimal trajectory to follow. Fifth order polynomial has been known as a good analytical estimation of desired trajectory [8], and trapezoidal acceleration profile resultant trajectory has been known as generating the least possible lateral acceleration on the vehicle [9]. In this research, a direct trajectory optimization of the vehicle is proposed in which the performance index minimizes lateral acceleration, while meeting some additional required terminal criteria. The results from this controller are compared to trajectories used by previous researchers: 1) analytical 5th order polynomial and 2) trapezoidal acceleration profile trajectories.

The proposed method can be used for different tasks such as automated lane change maneuver, and controlling the vehicle in the presence of disturbances. Also the desired trajectory and lateral acceleration profile can be shaped by choosing the weights or modifying the performance index. Moreover, this method can be extended to include effect of nonlinearities in the system to make a successful maneuver.

II. METHOD

A. Dynamic Model and Control method

A 2-DOF bicycle model [2, 5, 7, 9] of the vehicle was selected. Figure 1 shows the schematic of this model. Road irregularities, aerodynamics effects, load transfer and other nonlinearities were ignored, and dynamic parameters of a Ford Taurus model 1992 are used. Using assumptions of constant forward velocity, and front wheel steering, the equations of motion of this system are:

\[
\frac{d}{dt} \begin{bmatrix} \dot{y} \\ \dot{x} \end{bmatrix} = \begin{bmatrix} \frac{-2C_{af} + 2C_{ar}}{mV} & \frac{-V_y + 2C_{af}f_l - 2C_{ar}f_r}{mV} \\ \frac{-2C_{af}f_l + 2C_{ar}f_r}{I_y} & \frac{2C_{af}f_r - 2C_{ar}f_l}{I_y} \end{bmatrix} \begin{bmatrix} \dot{y} \\ \dot{x} \end{bmatrix} + \begin{bmatrix} \frac{2C_{af}}{m} \\ \frac{2C_{af}f_r}{I_y} \end{bmatrix} \frac{\rho}{\rho_0} \sin(\phi) \tag{1} \]

These equations combined with the following equations for location of the vehicle represent steering system.

\[
\begin{align*}
\dot{Y} &= V \sin(\phi) + V \cos(\phi) \\
\dot{X} &= V \cos(\phi) - V \sin(\phi) \\
\dot{\psi} &= \tau \\
\end{align*} \tag{2-4}
\]

The purpose of the optimization in this study is to perform the desired maneuver (i.e. lane change or evasive), while meeting other requirements subject to constraints. The final desired requirements are: 1) to reach the desired lateral position, 2) to have zero steering input, and 3) the vehicle to be in the straight line at the end of the maneuver, while minimizing the lateral acceleration.

\[
f = \int_0^\tau \rho \frac{a^2}{2} \frac{\alpha}{dt} + \rho_0 \alpha r_{max} \tag{5} \]

s.t. terminal constraints: \( \phi(\tau_f) = 0, Y(\tau_f) = 3.66 \), \( u(\tau_f) = 0 \)

This optimization problem can be solved with collocation technique by calculating state variables from solution of

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ordinary differential equations until the minimum of the performance index is reached.

B. Comparing to other controllers

First different trajectories that have been used by other researchers will be investigated and compared based on standard criteria such as critical velocity of the vehicle, and maximum lateral acceleration required to perform a specific maneuver. Based on the result from this part, the best existing virtual desired trajectory will be selected to be used in the second part of the research. In the second part several selected controllers such as Proportional-Integral-Derivative controller (PID controller), and Linear quadratic regulator (LQR), other optimal controls and various non-linear controllers, (e.g sliding mode control, etc.) will be developed to make the vehicle to follow the maneuver. The controllers will be compared in following trajectories for various evasive maneuvers, obstacle avoidance, and negotiating curves using a full vehicle dynamic model as a plant.

C. Comparing to expert human drivers

The results from simulations will be compared to the ones obtained from experimental evasive maneuver tests, where final time and maximum steering rate will be set to the same values achieved by experienced drivers [3].

D. Comparing to virtual desired trajectories

Results of the trajectory optimizations will be compared to those of ideally tracking a virtual desired trajectory at various velocities. These trajectories were analytical solution of 5th order polynomial, and trapezoidal acceleration profile. 5th order polynomial is a very good analytical representation of desired trajectory for this kind of maneuvers [10]. Also, using jerk as the input to generate trapezoidal acceleration profile (TAP) has been suggested by some other researchers [8, 11].

III. PRELIMINARY RESULTS

A. Final time 1.6 sec, velocity 16.7 m/s (60 Km/h, 37 mph)

Figure 2 (a, b) shows the resultant trajectory and steering angle input from simulation with velocity of 16.67 m/s and final time of 1.6 sec with steering gear ratio of 15.

![Figure 2](Image)

**FIGURE 2. (A) TRAJECTORY GENERATED BY THE DIRECT OPTIMIZATION METHOD TO AVOID AN OBSTACLE (B) STEERING ANGLE INPUT**

Figure 3 shows the comparison of lateral acceleration profile from the direct trajectory optimization method suggested in this study, and two virtual desired trajectories: 5th order polynomial, and trapezoidal acceleration profile.

![Figure 3](Image)

**FIGURE 3. COMPARISON OF LATERAL ACCELERATION PROFILE OF 5TH ORDER POLYNOMIAL, TAP, AND DIRECT TRAJECTORY OPTIMIZATION**

IV. FUTURE WORK

To have valid results for higher lateral accelerations generated in evasive maneuvers, a more complicated model with nonlinear tire model and rollover modeling will be developed for nonlinear controllers.

REFERENCES


NOMENCLATURE

- $a_y$: Lateral acceleration
- $l_f$ or $l_r$: Distance from front (rear) axle to c.g. of the vehicle
- $C_{aw}$ or $C_{aw}':$: Cornering stiffness of the front (rear) wheels
- $V_x$: Forward velocity of the vehicle
- OXY: Global coordinate system
- $\alpha_f$ or $\alpha_r$: Front (rear) wheel slip angle
- $\delta$: Steering angle
- $\psi$: Yaw angle