ABSTRACT

High Speed Obstacle Avoidance at the Dynamic Limits for Autonomous Ground Vehicles

by

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Enabling autonomy of passenger-size and larger vehicles is becoming increasingly important in both military and commercial applications. For large autonomous ground vehicles (AGVs), the vehicle dynamics are critical to consider to ensure vehicle safety during obstacle avoidance maneuvers especially at high speeds. This research is concerned with large-size high-speed AGVs with high center of gravity (CoG) that operate in unstructured environments. The term 'unstructured' in this context denotes that there are no lanes or traffic rules to follow. No map of the environment is available *a priori*. The environment is perceived through a planar light detection and ranging sensor. The mission of the AGV is to move from its initial position to a given target position safely and as fast as possible.

In this dissertation, a model predictive control (MPC)-based obstacle avoidance algorithm is developed to achieve the objectives through an iterative simultaneous optimization of the path and the corresponding control commands. MPC is chosen because it offers a rigorous and systematic approach for taking vehicle dynamics and safety constraints into account.

Firstly, this thesis investigates the level of model fidelity needed in order for a MPC-based obstacle avoidance algorithm to be able to safely and quickly avoid obstacles even when the vehicle is close to its dynamic limits. Five different representations of vehicle dynamics models are considered: four variations of the two Degrees of-Freedom (DoF) representation as lower fidelity models and a fourteen DoF representation with combined-slip Magic Formula tire model as a higher fidelity model. It is concluded that the two DoF representation that accounts for tire nonlinearities and longitudinal load transfer is necessary for the MPC-based obstacle avoidance algorithm in order to operate the vehicle at its limits within an environment that includes large obstacles. For less challenging environments, however, the two DoF representation with linear tire model and constant axle loads is sufficient.

Secondly, existing MPC formulations for passenger vehicles in structured environments do not readily apply to this context. Thus, a novel nonlinear MPC formulation is developed. First, a new cost function formulation is used that aims to find the shortest path to the target position, since no reference trajectory exists in unstructured environments. Second, a region partitioning approach is used in conjunction with a multi-phase optimal control formulation to accommodate the complicated forms the obstacle-free region can assume due to the presence of multiple obstacles along the prediction horizon in an unstructured environment. Third, the no-wheel-lift-off condition, which is the major dynamical safety concern for high-speed, high-CoG AGVs, is established offline using a fourteen DoF vehicle dynamics model and is included in the MPC formulation. A formulation is first developed by assuming a constant-speed operation. It is then extended with the capability of simultaneous optimization of both steering angle and reference longitudinal speed commands. Simulation results show that the proposed algorithm is capable of safely exploiting the dynamic limits of the vehicle while navigating the vehicle through sensed obstacles of different size and number.

Thirdly, in the algorithm, a model of the vehicle is used explicitly to predict and optimize future actions, but in practice the model parameter values are not exactly known. Thus, the robustness of the algorithm to parametric uncertainty is also evaluated. It is demonstrated that using nominal parameter values in the algorithm leads to safety issues in about one fourth of the evaluated scenarios with the considered parametric uncertainty distributions. To improve the robustness of the algorithm, a novel double-worst-case formulation is developed that simultaneously accounts for the robust satisfaction of the two safety requirements of high-speed obstacle avoidance: collision-free and no-wheel-lift-off. Results from simulations with stratified random scenarios and worst-case scenarios show that the double-worst-case formulation considering both the most likely worst-case scenarios and the less likely worst-case scenarios renders the algorithm robust to all uncertainty realizations tested. The trade-off between the robustness and the task completion performance of the algorithm is also quantified.

Finally, in addition to simulation-based validation, preliminary experimental validation is also performed. These results demonstrate that the developed algorithm is promising in terms of its capability of avoiding obstacles. Limitations and potential improvements of the algorithm are discussed.