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A model predictive speed tracking control approach for autonomous ground vehicles

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ABSTRACT

This paper presents a novel speed tracking control approach based on a model predictive control (MPC) framework for autonomous ground vehicles. A switching algorithm without calibration is proposed to determine the drive or brake control. Combined with a simple inverse longitudinal vehicle model and adaptive regulation of MPC, this algorithm can make use of the engine brake torque for various driving conditions and avoid high frequency oscillations automatically. A simplified quadratic program (QP) solving algorithm is used to reduce the computational time, and the approach has been applied in a 16-bit microcontroller. The performance of the proposed approach is evaluated via simulations and vehicle tests, which were carried out in a range of speed-profile tracking tasks. With a well-designed system structure, high-precision speed control is achieved. The system can robustly model uncertainty and external disturbances, and yields a faster response with less overshoot than a PI controller.

1. Introduction

Autonomous ground vehicles, as an important part of intelligent transportation system (ITS), are attracting more attention than ever before. Their control system usually consists of three modules: environment perception, planning and decision-making, and vehicle control [1–5]. The environment perception module obtains information on surroundings by external sensors, such as lasers, cameras and radar, and then fuses the information by building environment maps to determine drivable surfaces. The planning and decision-making module gathers and handles task information, and combines it with vehicle states and drivable surfaces information to determine the desired path and the speed profile. The vehicle control module coordinates the engine, brakes and steering to track the desired path and speed.

For autonomous ground vehicles, the desired speed is determined by a variety of factors. For instance, the robot Stanley, which won the 2005 DARPA Grand Challenge, uses path planner, health monitor, and speed recommender to set the desired vehicle speed [2]. The speed tracking control system needs to track the desired speed precisely, especially when autonomous ground vehicles are conducting complex tasks, such as autonomous overtaking. This structure can simplify the control system of autonomous ground vehicles, so the planning and decision-making module can focus on determining the desired path and the speed profile and make more sophisticated decisions. Other longitudinal vehicle control methods, such as adaptive cruise control (ACC), stop and go (SG), and full speed range adaptive cruise control (FSRA), always work with a human driver and just follow the movements' trend of the preceding vehicle [6–8].

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Nomenclature

a, a_{des}	the actual and desired vehicle accelerations
f_b	the function between a and p_b
f_{tr}, $f_{tr,0}$	the torque ratio and the stall torque ratio
F_{xdes}	the desired longitudinal force
H, G	the factors for QP problem
H_p, H_c	the prediction and control horizons
i_g, i_o	the ratio of transmission and the ratio from transmission output shaft to wheel
K, τ	the system gain and time constant
k	the current sampling time
k_b	the proportional coefficient of the applied brake torque to the brake master cylinder pressure
k_c	the coefficient of p_{bdes} to $-a_{des}$ ($a_{des} < 0$)
k_f, k_r	the proportional coefficient in a single side of the front/rear axle
k_P, k_I	the gains for the PI controller
k_α, k_β	the proportional coefficients of the actuator control inputs to the speed error metric
m	the vehicle mass include sprung mass and unsprung mass of both axles
n_e	the engine speed
n_t, n_o	the transmission input shaft speed and output shaft speed
p_b, p_{bdes}	the actual and desired brake master cylinder pressures
Q, R, S	the weighting matrices of the system output, control increment and control input
r_w	the effective radius of wheel
S_{tc}, $S_{tc,1}$	the speed ratio of torque converter and a given speed ratio when $f_{tr}=1$
T	the sampling period
T_{bdes}	the desired brake torque
T_{cdes}	the desired torque at the output side of torque converter
T_{edes}	the desired engine output torque
T_{emax}	the maximum engine torque
u	the control input
u_{min}, u_{max}	the acceleration limits
u_{PI}	the speed error metric
v, v_{ref}	the actual and desired vehicle speeds
α_{th}, α_{thdes}	the throttle control input and the desired throttle angle
β_{th}	the normalized brake control input
η_T	the powertrain efficiency
Δu^*	the optimal input increment
$\Delta u_{min,acc}$, $\Delta u_{max,acc}$	the acceleration increment limits in the drive mode
$\Delta u_{min,dec}$, $\Delta u_{max,dec}$	the acceleration increment limits in the brake mode
Δu_{min}, Δu_{max}	the limits of the final acceleration increments

Subscripts

qp	the Matlab QP solver quadprog was used
simp	the simplified QP solving algorithm was used
lpd	α_{th} is obtained from the look-up table of inverse engine map
elpd	α_{th} is obtained by a simplified engine mode

Some approaches have been proposed to enhance the speed tracking accuracy. Even if the gains of conventional PI/PID controller are well tuned for some operating regions, it is likely to demonstrate inferior performance in other conditions due to the severe nonlinearities present in the system. As a result, overshoot cannot be avoided, and the response is sluggish in most driving conditions [9,10]. Yanakiev et al. [9] introduced a signed quadratic (Q) term into the PID and adaptive PI controllers and used the proposed PIQD and adaptive PIQ controllers to reduce speed overshoot. The authors suggested that the response time becomes longer with reduced control gains. Hunt et al. [10,11] used a generalized gain scheduling approach to design a high precision speed controller. Proper selection of the observer polynomials is significant for making the controller insensitive to the measurement noise and un-modeled high frequency dynamics. Anderson proposed a Speed-based Acceleration Maps (SpAM)+PI controller to track the speed of an autonomous ground vehicle [12]. Although this configuration allows for a faster response with less overshoot than a PI controller, Anderson did not recommend implementing the approach because the generation of speed maps is both time consuming and sensitive to less than perfect data. Moreover, the throttle will oscillate causing a jerky ride when tracking a constant speed. Wang et al. [13] developed a nonparametric controller with an internal model control (IMC) structure for the longitudinal speed tracking control. The comparisons with SpAM+PI indicate that this system can track speeds in a wider range and yield an acceptable precision, but it is difficult to obtain an accurate nonparametric dynamical model for all the inputs. Fuzzy logic controller does not require a detailed model of the system, but considerable vehicle tests and parameter calibrations are needed to create a rule library that is large enough for use [14–17]. Kim et al. [1] developed a time-varying parameter adaptive vehicle speed controller that does not rely on a relatively accurate vehicle model, but its adaptation gains need to be tuned carefully to avoid high frequency oscillations. Murayama and Sakai et al. [18,19] applied a nonlinear model predictive control (NMPC) scheme for a torque demand control for speed tracking in vehicles with a variable valve lift engine, which is implemented by controlling the throttle angle, variable valve lift, ignition timing, and fuel injection directly. However, those control variables are not available for most researchers.

Like most other longitudinal vehicle control schemes, the proposed speed tracking controller has an upper level controller and a lower level controller. The upper level controller calculates the desired acceleration that "smoothly" and "quickly" track the desired speed profile. The lower level controller controls the engine and brakes to reach the desired acceleration [6,7,20]. The difference is that the proposed lower level controller does not need to track the desired

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