Mechanical Systems and Signal Processing 90 (2017) 154–174

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Dynamics control of autonomous vehicle at driving limits and experiment on an autonomous formula racing car

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ARTICLE INFO

Article history:
Received 2 August 2016
Received in revised form 22 October 2016
Accepted 13 December 2016

Keywords:
Autonomous vehicle
Electric vehicle
Path following
Limit driving
Vehicle dynamics control

ABSTRACT

In this paper, a novel dynamics controller for autonomous vehicle to simultaneously control it to the driving limits and follow the desired path is proposed. The dynamics controller consists of longitudinal and lateral controllers. In longitudinal controller, the G-G diagram is utilized to describe the driving and handling limits of the vehicle. The accurate G-G diagram is obtained based on phase plane approach and a nonlinear vehicle dynamic model with accurate tyre model. In lateral controller, the tyre cornering stiffness is estimated to improve the robustness of the controller. The stability analysis of the closed-looped error dynamics shows that the controller remains stable against parameters uncertainties in extreme condition such as tyre saturation. Finally, an electric autonomous Formula race car developed by the authors is used to validate the proposed controller. The autonomous driving experiment on an oval race track shows the efficiency and robustness of the proposed controller.

1. Introduction

Autonomous driving technology has become a major focus in automotive industry. As reported in [1], more than 90% accidents are caused by human errors. Autonomous driving technology is expected to reduce driver errors, avoid potentially dangerous situations and reduce driver's workload [2–4]. The impressive performance of the participant autonomous vehicles in 2007 DARPAR challenge competition has proved the possibility of autonomous driving to be true in the near future [5–7]. Moreover, autonomous driving is also important focus in military field, several autonomous combat vehicles have been developed to conduct the task of searching, rescuing or light combating [8,9].

The software system of autonomous vehicle includes environment recognition system, path and motion planning system, dynamics and motion control system [10,11]. Apparently, much more sophisticated sensors are needed to achieve autonomous driving, such as cameras, radars or GPS/INS system [12–14]. Many researchers have reported the work on overall architecture and the possibility of autonomous driving [15,16]. In this paper, the dynamics and motion control of the autonomous vehicle will be focused on.

The dynamics and motion control of autonomous vehicle aims at eliminating the path error between the actual location and the desired path, as well as assuring the handling stability during the motion. It derives from the research of nonholonomic problem in robot field [17]. However, in recent years, researchers mainly use hierarchical architecture control to reduce the complexity of the controller design [18]. Early works on dynamics control system data back to the Anti Brake

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http://dx.doi.org/10.1016/j.ymssp.2016.12.017
0888-3270/

Nomenclature

a_x	the longitudinal acceleration of the vehicle
a_y	the lateral acceleration of the vehicle
a_{xmaxB}	the maximum ideal negative acceleration
a_{ymax}	the maximum ideal lateral acceleration
a_{xmaxT}	the maximum ideal positive acceleration
B	the track width of the vehicle
B_1	the stiffness factor of Magic Formula
c	the rate of curvature change
c_a	the actual tyre cornering stiffness.
c_f	the cornering stiffness of front tyre
c_f	the cornering stiffness of rear tyre
c_n	the nominal tyre cornering stiffness
C_1	the shape factor of Magic Formula
D	the peak factor of Magic Formula
e_p	the projected error
E	the curvature factor of Magic Formula
F_x	the pure longitudinal force of Magic Formula
F_y	the pure lateral force of Magic Formula
F_{x0}	the combined longitudinal of Magic Formula
F_{y0}	the combined lateral of Magic Formula
F_{xii}	the longitudinal force of 4 tires
F_{yii}	the lateral force of 4 tires
F_{zii}	the vertical load of 4 tires
h	the height of C.G
h_{rf}	the roll center of front suspension
h_{rf}	the roll center of rear suspension
I_w	the yaw moment inertia.
I_z	the yaw inertia of the vehicle
K_1	the feedback gain of longitudinal controller
K_2	the feedback gain of lateral controller
K_3	the feedback gain of lateral controller
$K_{\Phi f}$	the roll stiffness of front suspension
$K_{\Phi f}$	the roll stiffness of rear suspension
l_f	the distance from C.G location to front axle
l_r	the distance from C.G location to rear axle
L	the wheelbase of the vehicle
m	the mass of the vehicle
r	the yaw velocity of the vehicle
R_t	the radius of tyre
s	the tyre longitudinal slip ratio.
s_i	the distance measured along clothoid segment
T_i	the torque of the motor acting on 4 wheels
U_x	the longitudinal speed of the vehicle
U_{xa}	the actual vehicle speed
U_{xd}	the desired vehicle speed
U_{xentry}	the desired entry speed
U_y	the lateral speed of the vehicle
x_p	the projected distance
X	the slip ratio or slip angle in Magic Formula
α	the lateral slip angle
β	the side slip angle of the vehicle.
δ	the front wheel steer angle
μ_{max}	the maximum road friction coefficient
μ_{max}	the ideal average maximum friction coefficient
σ	the normalized combined slip ratio
σ_x	the normalized longitudinal slip ratio
σ_y	the normalized lateral slip angle
Φ	the heading angle of the vehicle
Φ_p	the heading angle of the desired path
ω_i	the rotation speed of 4 wheels