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Asymptotically stable path following for lateral motion of an unmanned ground vehicle

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ABSTRACT

This study proposes an asymptotically stable path following controller for autonomous navigation of an unmanned ground vehicle (UGV) using vector field and robust-integral-signum error (RISE) feedback. The path following controller is divided into two parts: one part generating a heading command and another part designing a robust control. To determine the reference heading command under various uncertainties, the vector field method is employed, and then the RISE feedback controller is designed to follow the heading command. Finally, experiments are conducted on paved and unpaved roads to validate the effectiveness of the proposed method.

1. Introduction

Autonomous navigation of unmanned ground vehicles (UGVs) is a challenging problem and an increasingly important topic since future vehicle systems will have to cooperate with humans in an unpredictable environment. This implies that UGVs are clearly required to operate robustly and safely in an uncertain environment, while interacting in various ways with people. Thus, a great deal of research has been actively performed for the last two decades. First, researchers pursued the development of automated highway systems, in which vehicles depend significantly on the highway infrastructure to guide them (Ioannou, 1999). The second research thrust was to develop both semi-autonomous and autonomous vehicles that depend little, if at all, on highway infrastructure (Lantos & Mirton, 2011).

In the beginning, researchers put their efforts into developing automated highway systems (Ioannou, 1999), in which the vehicles heavily depend on the highway infrastructure to guide them. To address issue, more research focus was shifted to develop both semi-autonomous and autonomous vehicles that depend little, if at all, on the highway infrastructure (Lantos & Mirton, 2011), and recently, the first trial of the autonomous vehicles in open public space was performed (Broggi et al., 2014). From 2003 to 2007, the U.S. Defense Advanced Research Projects Agency (DARPA) held three Grand Challenges that remarkably accelerated the development of autonomous vehicle technology and reignited the public attention (Buehler & Iagnemma, 2008; Iagnemma & Buehler, 2006a, 2006b, 2008).

To navigate autonomously in an unpredictable environment, the UGVs generally have real-time world or local environment modeling system based on the information data from various sensors, because it is unlikely that they obtain their environment information exactly in advance. This modeling is transmitted to local path planning (LPP) system, and the LPP system generates an appropriate reference path set for the ultimate goals of the given mission. Next, the path following control component generates heading and velocity commands to satisfy the reference path set, and the determined heading and velocity references are then followed using various control techniques. This study concentrates how to generate the reliable heading command, satisfying the reference path set, and to follow the heading command asymptotically. In order to do so, this study utilizes the environment modeling and LPP systems developed by the authors' laboratory, and those two systems conceptually make use of the methods developed in Szeliski (2010), Matthies and Elfes (1988), Hundelshausen, Himmelsbach, Hecker, Mueller, and Wuensche (2008), and Besiadecki, Leger, and Maimone (2007). Moreover, it is assumed that the velocity reference is properly determined and maintained by the separate controller because the decoupled control system, composed of the velocity and heading controllers, can have satisfactory navigation performance (Hundelshausen et al., 2008; Kuwata et al., 2009; Thrun et al., 2006; Urmson et al., 2006). The path following controller in this study is designed for the lateral motion of the UGV only.

To determine the heading command for the given reference path set, this study utilizes the vector field method, which enables the UGV to be on the path rather than at a certain point at a specific time. The vector field method has been extensively studied in the aerospace research field to satisfy the given control objective (Sujit, Saripalli, & Sousa, 2014). An flight control problem for unmanned aerial vehicles (UAVs) was solved using the vector field method (Lawrence, Frew, & Pisano, 2008), and their cooperation problem

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Nomenclature

ψ	heading angle
r	angular rate
β	slip angle of center of gravity (C.G)
v_x	longitudinal velocity
δ	steering angle
m	vehicle mass
I_z	moment of inertia about the z-direction
F_{x_f}	longitudinal force of the front axle
F_{y_f}	lateral force of the front axle
F_{y_m}	lateral force of the middle axle
F_{y_r}	lateral force of the rear axle
c_f	cornering stiffness of the front wheel
c_m	cornering stiffness of the middle wheel
c_r	cornering stiffness of the rear wheel
β_f	slip angle of the front wheel
β_m	slip angle of the middle wheel
β_r	slip angle of the rear wheel
l_f	distance between the C.G. and front axle
l_m	distance between the C.G. and middle axle
l_r	distance between the C.G. and rear axle

was addressed in Frew, Lawrence, and Morris (2008). The path following methods for UAVs were presented in Rysdyk (1999) to provide a constant line of sight between the UAV and observed target, and Nelson, Barber, Mclain, and Beard (2007) presented the line, orbit tracking or combined maneuver of line and orbit tracking for UAV. Recently, the research of the UAV navigation with a fuzzy model was developed to conserve total energy requirements (Kladis, Economou, Knowles, Lauber, & Guerra, 2011). In the UGV research field, the vector field method was employed for the formation control problem of the UGV (Kwon & Chwa, 2012) where the heading reference for the follower UGV is determined by utilizing the exactly known information on leader's position and predefined radius of the rotation. In addition, the research about the autonomous motorcycle was performed by utilizing the vector field-based maneuver regulation (Zhang & Yi, 2010). However, the methods developed in the various references cannot be directly utilized in the authors' study since the off-road UGV operates under changing uncertain environmental conditions.

To cope with this situation, this study modifies the previous approach in Nelson et al. (2007) and Kwon and Chwa (2012). First, two proper points are chosen among the reference path set given from the LPP system. These two points determine an orbit, and the vector field for converging the orbit is generated. The heading reference is, then determined to be on the vector field. Unlike the pure pursuit method (Kuwata et al., 2009; Thrun et al., 2006; Urmson et al., 2006) that utilizes one reference point, the heading command based on the vector field is less sensitive to the dynamically changing environment because it takes more information from the reference path set. That is, it is not trivial problem to choose one proper reference point consistently under the uncertain environment.

The determined heading reference can be followed by the classic control methods such as the proportional-derivative (PD) (Frew et al., 2008; Kwon & Chwa, 2012; Thrun et al., 2006) or proportional-integral-derivative (PID) controller (Urmson et al., 2006). However, if some uncertainties are included in the dynamic system, its performance can degrade without consideration of those uncertainties. This performance degradation can be recovered by using various control techniques. In Zhang, Zhang, and Wang (2014), the robust gain scheduling method was proposed to control the nonlinear vehicle with the time varying model. The electric vehicle with the independently actuated four wheels was controlled by the linear time varying controller in Wang, Zhang, and Wang (2014) and Huang, Zhang, Zhang, and Wang (2014) studied the later motion controller to consider the steering system with the backlash-type hysteresis. While the above studies considered the linear time varying models to handle the uncertainties in the vehicle, the robust controller for the nonlinear system can be directly designed using the sliding mode control (Khalil, 2002). Since the sliding mode term based on a sign function generates the chattering phenomenon in the control input, the saturation function is commonly employed to remove the discontinuity in the control input. Even though the saturation function-based sliding mode term assures both the performance improvement and continuity of the control input, it is not possible to prove the asymptotic stability of the closed-loop system with the saturation function analytically, because it is an ad hoc method to avoid the discontinuity problem.

In this study, the robust-integral-signum-error (RISE) feedback term developed in Xian, Dawson, de Queiroz, and Chen (2004) is utilized to follow the heading reference command. The RISE feedback controller assures both the asymptotic stability and continuous control input analytically by integrating the signum error function without utilizing the saturation function. In Patre, MacKunis, Kaiser, and Dixon (2008), the gain of the RISE feedback controller was reduced by including neural network (NN) feedforward terms, and Patre, MacKunis, Johnson, and Dixon (2010) utilized the concept of the composite adaptive control with the NN. The performance of the RISE feedback has been validated in various applications, such as neuromuscular electrical stimulation problem (Sharma, Stegath, Gregory, & Dixon, 2009), unmanned helicopter (Shin, Kim, Kim, & Dixon, 2012), hypersonic aircraft (Wilcox, MacKunis, Bhat, Lind, & Dixon, 2010), and etc. In this study, the RISE feedback controller in Xian et al. (2004) is adopted to follow the vector field-based heading command. In addition, the nominal dynamic information of the UGV is supplemented to the RISE feedback controller, i.e., the dynamic model inversion is utilized (Shin et al., 2012). Since the cancellation of the nominal dynamic terms reduces the magnitude of the bounding function which suppresses the uncertain terms in the closed-loop system, the region of attraction is increased without the increment of the RISE feedback gain.

In summary, this study proposes the method to generate the heading command using the vector field method with the varying circle, and then, the asymptotically stable path following algorithm is developed to follow the given heading commands by utilizing the RISE feedback control with the nominal dynamic model information.

This paper is organized as follows. The lateral dynamic vehicle model of the UGV is described and its internal stability is analyzed in Section 2. Section 3 presents the method to generate the vector field and determine the heading reference command. The RISE feedback controller based on the nominal model of the UGV is developed in Section 4. To validate the effectiveness of the proposed method, Section 5 describes results of experiments performed in the Proving Ground. Finally, the conclusion of the study is presented in Section 6.

2. Dynamic vehicle model

In general, it is not trivial to design the controller for the UGV using the full nonlinear dynamics because there exist lots of highly nonlinear terms such as interactive forces between the UGV and ground, and coupling effect between longitudinal and lateral motions. Therefore, the highly nonlinear terms are simplified as the linear elements, and the dynamic model with the linear terms