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ASOC 3485 1–11

Applied Soft Computing xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Soft Computing

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

High-speed autonomous navigation system for heavy vehicles

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ARTICLE INFO

Article history:
Received 24 December 2014
Received in revised form 29 January 2016
Accepted 14 February 2016
Available online xxx

Keywords:
Autonomous vehicles
Navigation
Heavy vehicles
Fuzzy control
Differential GPS
Sensor data fusion

ABSTRACT

This paper presents techniques for GPS based autonomous navigation of heavy vehicles at high speed. The control system has two main functions: vehicle position estimation and generation of the steering commands for the vehicle to follow a given path autonomously. Position estimation is based on fusion of measurements from a carrier-phase differential GPS system and odometric sensors using fuzzy logic. A Takagi–Sugeno fuzzy controller is used for steering commands generation, to cope with different road geometry and vehicle velocity. The presented system has been implemented in a 13 tons truck, and fully tested in very demanding conditions, i.e. high velocity and large curvature variations in paved and unpaved roads.

1. Introduction

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Autonomous guidance of ground vehicles has been an active research and development topic in the last 30 years. For example, several systems have been implemented in experimental outdoor autonomous vehicles such as the Navlab family at Carnegie Mellon University [1], the ARGO autonomous vehicle [2], the ROMEO vehicles [3]. The interest in autonomous vehicles' technologies has grown specially in the US, where DARPA has organized the Grand Challenges and the Urban Challenge from 2004 to 2007 [4,5], which remarkably promoted the technologies of intelligent vehicles around the world. Reference [6] presents the main autonomous vehicles developed in the last years in the US. Other remarkable examples in the last years are the VisLab autonomous vehicles [7,8]. Most of these vehicles are the result of the adaptation of conventional cars or vans. However, the number of references presenting experimental results with autonomous heavy vehicles, such as trucks, is lower.

Interest in heavy vehicle autonomous guidance has grown from the nineties in the framework of the initiatives on intelligent transportation systems (ITS) and automated highway systems (AHS). Published results on autonomous heavy vehicles come mainly from the California PATH program [9–11] and University of Minnesota's SAFETRUCK [12–14]. Other work on autonomous heavy vehicles has been done with TERRAMAX [15,16], designed for off-road navigation, and by Isuzu Motors in Japan [17]. Recently, special attention has been devoted to vehicle platooning or semi-autonomous "road trains" [18], composed by a leader vehicle with a human driver with one or several autonomous vehicles following it closely, for its potential in fuel and emissions savings and increase of road capacity. The SARTRE European Project has made a road demonstration of a platoon with a leader truck and several vehicles following it [19,20]. Tests with a three truck platoon have been performed within the Energy ITS Project in Japan [21,22]. Other examples include the German KONVOI project which analyzes the implications of truck platoons in autobahns [23] and the Swedish research program on intelligent vehicles [24].

Many of these autonomous vehicle researches have been done at medium or low speeds. High speed navigation of autonomous vehicles is still a challenging application due to the requirements on reliability and safety.

The choice of the sensors used for position estimation in autonomous navigation may have important practical requirements. Some sensors require auxiliary guidance mechanisms in or around the field of interest [25], as is the case with most of PATH program work [13], which uses magnetic markers buried in the road. The work in [17] also uses magnetic markers, but it stores a "map" of the markers for preview control.

This paper deals with GPS based autonomous navigation by implementing a sensor data fusion and path following techniques.

With the advent of modern GPS receivers, kinematic centimeter-level absolute position estimation and attitude measurements of the vehicle are available using carrier-phase differential global

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http://dx.doi.org/10.1016/j.asoc.2016.02.026
1568-4946/

Please cite this article in press as: A. Rodriguez-Castaño, et al., High-speed autonomous navigation system for heavy vehicles, Appl. Soft Comput. J. (2016), http://dx.doi.org/10.1016/j.asoc.2016.02.026

positioning system (DGPS) with position accuracy up to few centimeters. Carrier-phase DGPS techniques are being used for straight line tracking and heading control of golf carts and farm vehicles at low velocities [25], and adapted to conventional cars [26]. The TerraMax autonomous heavy vehicle [15] uses 3 different DGPS receivers for improved reliability. However, the use of GPS receivers requires operation environments with good sky visibility. Furthermore, in practical implementations, also arise other sources of errors like communication loss of differential correction messages, output variable latency and receiver errors [13]. Some of them can be detected taking into account the vehicle dynamics, using model-based fault detection and identification techniques, as is described in [14], and in [27] for an aerial vehicle. It has been also recognized that sensor data fusion can improve significantly the reliability of position estimation. Sensor data fusion for vehicle position estimation can be solved by means of statistical approaches, such as Kalman filtering (see, for example, [28]). These techniques require a stochastic state-space representation of the vehicle model and of the measurement process. A kinematic model of the vehicle and knowledge of measuring equipment are typically used to derive the state-space representation, although for nonlinear systems an extended Kalman filter formulation is needed. However, a main drawback of Kalman filtering is that sensor noise is modeled as white noise. Although this can be accurate for several sensors, it is clearly not true for DGPS. Moreover, the implementation of Kalman filtering requires estimations of the measurement covariance matrix, which can be obtained from the technical characteristics of the sensor equipment, and the process covariance matrix, that represents the model inaccuracies, which is much more difficult to obtain. It has been also shown that a poor estimation of input noise statistics may seriously degrade Kalman filter performance and even cause filter divergence [29]. In this paper fuzzy logic is applied to position estimation without the need for precise information, which can be difficult or expensive to obtain.

The path following component of a vehicle controller has the mission of generating the vehicle's steering to track a previously defined path, by taking into account the vehicle's actual position and orientation and the constraints imposed by the vehicle and its low-level motion controller. Path following, which is sometimes referred to as "lateral control" or "path tracking", is directly related to the lateral vehicle motion and steering control. Vehicle control also involves speed control. Both are coupled problems. However, path following has been usually studied for constant velocity. Thus, the path following algorithm implements a steering control law by using the error between the current estimated vehicle position/orientation and the path to follow. The inputs of the path tracker are variables defining the state of the vehicle with respect to the path, and the output is the steering command to be executed by the low-level motion controller. Linear control methods have been successfully applied for vehicle automated steering [30,31]. However, if the linearization conditions are violated or nonlinearities in the steering mechanism or in the motion sensors exist, the tracking deteriorates. Nonlinear path following techniques, as Takagi–Sugeno (TS) fuzzy control, have shown good performance [26]. TS fuzzy systems are a special type of fuzzy systems in which the consequent part of the rules is not defined by a fuzzy membership function but by affine linear dynamic systems. A TS fuzzy model will approximate a nonlinear system by smoothly interpolating these affine local models. Fuzzy control can also be used to integrate the driving knowledge acquired in the form of if-then rules from an experienced driver, and TS driving control laws directly extracted from sensor data recorded while the vehicle is operated by a human driver [32]. Furthermore, design techniques that guarantee stability based on Lyapunov functions and other methods can be also applied [33–37].

Most path following methods have parameters related to the selection of a goal point, or a particular segment of the path to follow, which are required to compute the signal error in the path following loop. This has been integrated with path tracking through the concept of preview control. TS fuzzy logic also provides an efficient framework for integrating this parameter adaptation in the steering controller [38] and could be also implemented to tune automatically the parameters according to the current navigation conditions. This paper presents a Takagi–Sugeno fuzzy path following controller for heavy vehicles at high speeds, including fuzzy sensor data fusion for vehicle position estimation.

The remaining of the paper is organized as follows. Section 2 introduces the main characteristics of GPS-based path following. In Section 3 the Takagi–Sugeno fuzzy path following strategy is presented. Section 4 describes the experiments carried out with a 13 tons truck. Finally Section 5 presents the conclusions.

2. GPS based path following

2.1. Position estimation

GPS receivers provide low-frequency position information which is clearly insufficient to control a vehicle at high velocities. It is necessary to use additional high-frequency sensors to improve the performance and integrity of GPS navigation systems. A position estimation algorithm should use low-frequency sensor information for correcting low-frequency drift error in high frequency sensors and should use high frequency sensor information to decorrelate the errors in low-frequency sensors. Kalman filtering is one of the most widely used sensor data fusion technique in autonomous navigation.

This paper proposes the application of fuzzy sensor data fusion to consider the heuristic knowledge involved in the estimation problem. This technique is based on the use of a fuzzy system for the on-line fusion of the measurements from a tachometer, a gyroscope and a carrier-phase DGPS receiver. The proposed fuzzy position estimation system initially showed similar performance to the extended Kalman filter in experimental tests, but the fuzzy position estimation was much more flexible and easily tuned than the Kalman filter. This flexibility comes from the fact that a human designer can easily understand what each rule does and it is much easier to tune them to match experimental results.

The fuzzy position estimation system uses the data from the available sensors to obtain an estimation of the position and orientation of the truck in real time. The DGPS receiver provides data on latitude and longitude of the receiver antenna, which is then converted to Universal Transverse Mercator (UTM) coordinates. On the other hand, the gyroscope provides an estimation of the angular velocity of the vehicle, and the tachometer sensor readings are converted to linear velocity of the vehicle. With these measurements it is possible to obtain an incremental estimation of the position and orientation of the vehicle using the kinematic model.

At a first approximation and for short distances, the truck can be considered to move on a plane, and a simplified 2D model can be used. For navigation in 2D, the position and orientation of the vehicle is given by (x, y, θ) (see Fig. 1), where x and y are the vehicle's cartesian coordinates, θ is the orientation angle, and (v, ω) are the linear and angular velocities of the truck, respectively.

Then, the kinematic model is given by the following differential equations [3]:

$$\begin{aligned} \dot{x} &= -v \sin\theta \\ \dot{y} &= -v \sin\theta \\ \dot{\theta} &= \omega \end{aligned} \tag{1}$$

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