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Autonomous vehicle control using a kinematic Lyapunov-based technique with LQR-LMI tuning

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ABSTRACT

This work proposes the control of an autonomous vehicle using a Lyapunov-based technique with a LQR-LMI tuning. Using the kinematic model of the vehicle, a non-linear control strategy based on Lyapunov theory is proposed for solving the control problem of autonomous guidance.

To optimally adjust the parameters of the Lyapunov controller, the closed loop system is reformulated in a linear parameter varying (LPV) form. Then, an optimization algorithm that solves the LQR-LMI problem is used to determine the controller parameters. Furthermore, the tuning process is complemented by adding a pole placement constraint that guarantees that the maximum achievable performance of the kinematic loop could be achieved by the dynamic loop. The obtained controller jointly with a trajectory generation module are in charge of the autonomous vehicle guidance. Finally, the paper illustrates the performance of the autonomous guidance system in a virtual reality environment (SYNTHIA) and in a real scenario achieving the proposed goal: to move autonomously from a starting point to a final point in a comfortable way.

1. Introduction

Autonomous vehicles are gaining a huge popularity in society due to the technological innovation and safety increase with regard to current available vehicles. Between these improvements, one of the most important is the driving control system, which is responsible of generating comfortable and safe vehicle motion. In order to achieve such a right movement, a suitable control technique is needed. Model-based controllers are widely employed in many control applications where in the majority of the cases an elaborated modelling task is required.

Over the past decades, a lot of research effort has been dedicated to develop different vehicle models for control purposes. Kinematic models have been broadly used (Alcalá et al., 2016; Blažič, 2010; Rajamani, 2011) as well as lateral dynamic models (Hahn, Zindler, & Jumar, 2016; Rajamani, 2011; Soualmi, Sentouh, Popieul, & Debernard, 2014) and longitudinal dynamic models (Rajamani, 2011).

As it was expected, due to such model research progress many control techniques appear at the same time for solving the control problem in autonomous guidance. In Rajamani (2011), Hahn et al. (2016), Soualmi et al. (2014), Zhang and Wang (2016), Németh, Gáspár, and Bokor (2016) and Nguyen, Sentouh, and Popieul (2016) different types of lateral controls approaches are presented: PI, LPV (Linear Parameter Varying), T–S (Takagi–Sugeno) and MPC (Model Predictive Control).

In Marino, Scalzi, Orlando, and Netto (2009), a PID control approach is suggested for controlling the kinematic part of a vehicle. Kinematic control is also used in Alcalá et al. (2016), Indiveri (1999) based on Lyapunov approach obtaining promising results in slow velocity scenarios.

In the last decades, Lyapunov theory has become a standard rule for analysing stability of non-linear systems (Dixon, Dawson, Zergeroglu, & Behal, 2001; Freeman & Kokotovic, 2008), but also for obtaining model-based strategies for controlling the studied systems (Alcalá et al., 2016; Blažič, 2010; Dixon et al., 2001). In particular, when working with linear parameter varying (LPV) systems, a linear matrix inequality (LMI) expression can be used for checking Lyapunov stability. Such a LMI formalism has become a standard for analysis and control design in recent years (Duan & Yu, 2013).

LPV paradigm (Shamma, 2012) is nowadays considered a suitable strategy for embedding the system non-linearities inside varying parameters obtaining in this way a linear-like representation of a non-linear system. Such a formalism is appropriate to use linear control schemes for designing the controller.

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In this work, a non-linear kinematic Lyapunov-based control is proposed for solving both, the lateral and longitudinal control problem. An optimization algorithm for adjusting non-linear controller parameters is also proposed. This algorithm is based on formulating the closed-loop system in LPV form. Then, the Lyapunov controller parameters are obtained based on LQR-LMI approach. The idea behind the proposed tuning approach is rooted in the work of Farag and Werner (2004), where an approach for fixed structure controller is proposed splitting the problem into a convex and a non-convex sub-problems. A method for solving the convex sub-problem via LMIs is presented in El Ghaoui and Balakrishnan (1994).

In this paper, the trajectory generation, which uses a map and a global planner to compute the best trajectory for reaching the destination, is briefly presented. This trajectory is coarsely defined by a reduced number of global way-points, which are defined by its GPS coordinates and the vehicle orientation. In order to execute the manoeuvres comfortably, a local planner computes a smooth trajectory by adding intermediate local way-points defined by their GPS position, orientation and the desired linear and angular velocities.

Finally, the proposed techniques for vehicle motion control are first tested in a virtual reality environment (SYNTHIA). Then, a real on-field test scenario using an electric Tazzari vehicle is used for showing effectiveness in real conditions.

The paper is structured as follows: Section 2 presents and describes the electric Tazzari vehicle considered in the real scenarios. Section 3 introduces the vehicle model. The control design approach and its tuning are presented in Section 5. Section 4 describes the trajectory planning task. The simulation and experimental results are shown and commented in Sections 6 and 7. Finally, conclusions are stated in Section 8.

2. Vehicle description

The results presented in this paper are part of the project called *Elektra*[1] that aims to develop an autonomous vehicle. For such purpose, an electric Tazzari zero vehicle (Tazzari electric vehicle, 0000) is used (see Fig. 1). This system is a non-holonomic platform that can move like a normal road vehicle. This platform is composed by a set of sensors and actuators, as well as a PC and an electronic control unit (ECU) that manage all algorithms and communications between them. The diagram of the control architecture is depicted in Fig. 2. On one hand, the vehicle has on board an IMU–GPS and stereo cameras to obtain information about the environment and current state. Proper algorithms have to be employed in order to convert that crude information on convenient data for understanding the environment and localize the vehicle. On the other hand, a set of actuators are employed to perform the motion (steering and driven electric motors) as well as turning on the lights and opening doors. The rest of modules in Fig. 2 (perception, localization, planning and control) compose the software for performing the autonomous guidance task. This paper specially focuses on the non-linear automatic control module. However, the trajectory planning task is introduced for better understanding.

All the algorithms involved run over a trunk PC (6-core i7 5930 K, 32 GB DDR4) running ROS on GNU/Linux (Ubuntu distribution). An NVIDIA GTX Titan X board is used to run GPU-based algorithms for perception-image analysis.

The ECU, based on a Cortex-M4 MCU, runs a custom embedded software which communicates the PC control actions to the different car actuators (steering, throttle, brake, lights, horn), as well as reads the values of the car state sensors (steering, throttle, brake, speed, doors, battery).

The communication net is based on CAN bus protocol. Its cycle is currently set to 100 ms, which is sufficient for running all required algorithms.

[1] http://adas.cvc.uab.es/elektra/.

Fig. 1. Electric Tazzari Zero vehicle.

3. Vehicle modelling

The behaviour of the vehicle presented in Section 2 can be described by using equations that represent the kinematic and dynamic behaviour. In this section the development of the vehicle kinematic model is addressed for designing the control strategy. Kinematic model is based on the velocity vector movement in order to compute longitudinal and lateral velocities referenced to a global inertial frame.

3.1. Kinematic model

The kinematic model for the vehicle has been derived assuming that behaves as a bicycle-like vehicle. This is a quite standard assumption in the literature (Aicardi, Casalino, Bicchi, & Balestrino, 1995). Kinematic based model is widely used for control design because of its low parameter dependency. This model takes into account *yaw*, x and y motion while neglecting *roll*, *pitch* and z movements. Furthermore, its assumes null skidding and considers small lateral force. These two characteristics share the idea of travelling at low speed. The kinematic equations for the bicycle model are introduced below:

$$\begin{cases} \dot{x} = v\cos(\theta) \\ \dot{y} = v\sin(\theta) \\ \dot{\theta} = \omega \end{cases} \tag{1}$$

where x, y and θ represent the current position and orientation of the vehicle in metres and radians respectively, with respect to the global frame; v is the linear velocity and ω represents the angular velocity of the vehicle.

For developing the kinematic-based controller, an error model has been built. It is defined as the difference between real measurements (x, y and θ) and desired values (x_d, y_d and θ_d). However, this set of errors are expressed with respect to the inertial global frame (x, y in Fig. 3). For control purposes is suitable to express the errors with respect to the vehicle, such that lateral error is always measured in the lateral axis of the vehicle. Thus, a rotation over the road orthogonal axis is considered to represent the errors in the body vehicle frame (x_b, y_b):

$$\begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_d - x \\ y_d - y \\ \theta_d - \theta \end{bmatrix} \tag{2}$$

where subindexes d and e refer to desired and error values, respectively. For developing the error model is needed to take into account a non-holonomic constraint of the form:

$$\dot{x}\sin(\theta) = \dot{y}\cos(\theta) \tag{3}$$