# Control Laws for Autonomous Racing

Master's Thesis

**Author**: Bc. Dominik Filyó
**Supervisor**: doc. Ing. Martin Hromčík, Ph.D.
**Field of Study**: Cybernetics and Robobotics

Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Control Engineering

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# Declaration

I declare that the presented work was developed independently and that I have listed all sources of information used within it in accordance with the methodical instructions for observing the ethical principles in the preparation of university theses.

Bc. Dominik Filyó

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# Acknowledgements

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# Abstract

Fully autonomous driving under any conditions and circumstances is a challenging task on which experts from all over the world work. It is assumed that fully autonomous cars will not drive on the roads in the coming years. This thesis focuses mainly on a single part of the complex topic. The aim of this work is to explore existing control laws for autonomous vehicles and design a simple, yet robust control system for a racing car. The greatest emphasis is given to the classical control theory, although other methods are also mentioned here. After the control system is designed, it is validated and tested in the MATLAB environment. A sports vehicle Porsche 911 is selected as the test car due to its convenient properties.

Keywords: trajectory tracking, autonomous vehicle, autonomous racing, racing vehicle, vehicle control, longitudinal control, lateral control, vehicle dynamics

# Abstrakt

Pln¥ autonomní °ízení za jakýchkoli podmínek a okolností je náro£ný úkol, na kterém pracují odborníci z celého sv¥ta. P°edpokládá se, ºe v nadcházejících letech je²t¥ nebudou jezdit na silnicích pln¥ autonomní auta. Tato práce se zam¥°uje p°edev²ím na jednu £ást tohoto komplexního tématu. Cílem práce je prozkoumat existující °ídící zákony pro autonomní vozidla a navrhnout jednoduchý, ale robustní °ídicí systém pro závodní auto. Nejv¥t²í d·raz je kladen na klasickou teorii °ízení, i kdyº jsou zde zmín¥ny i jiné metody. Poté, co je °ídicí systém navrºen, je validován a testován v prost°edí MATLAB. Sportovní v·z Porsche 911 je vybrán jako testovací auto díky svým vhodným vlastnostem.

Klí£ová slova: sledování trajektorie, autonomní vozidlo, autonomní závod¥ní, závodní vozidlo, °ízení vozidla, podélné °ízení, p°í£né °ízení, dynamika vozidla

P°eklad názvu: •ídicí zákony pro autonomní sout¥ºní vozy

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# 1 Introduction

Cybernetics and robotics are one of the most perspective scientific areas in the world. Nowadays, more people are interested in modern technology than ever before. It is given by the fact that cybernetics influences our everyday lives since the new millennium. Let us mention the internet, where searching and advertisement are not imaginable without advanced knowledge in cybernetics, more specifically Artificial Intelligence (AI). Not everyone is interested in modern technology, but everyone must have noticed that robots are taking our jobs. According to [1], about 47 percent of US jobs were at risk in 2013 because of computerization. We can be sure that this trend will continue in the future.

This leads us to the topic of this thesis. Not only many employments are at risk, but also activities as driving. Huge research is being conducted at universities around the world. Czech Technical University in Prague (CTU), Faculty of Electrical Engineering (FEE) created a new centre for research of full authority vehicle control system layer named Smart Driving Solutions[1]. Not only car manufacturers invest billions of dollars in the development of self-driving cars. In 2019, investment into self-driving cars achieved $100 billion [2]. Companies that invested over $1 billion to autonomous driving are Volkswagen, Samsung, Ford, Toyota, Daimler, BMW, Audi, Honda, Softbank, Kia, Hyundai, Uber, Generals Motors and Apple (in descending order).

The main reason for the deployment of autonomous vehicles is the safety of passengers and pedestrians. A secondary goal is to make the journey more pleasant for passengers. With the expansion of wireless networks (5G), cars will be able to share information with other cars (car-to-car) and with infrastructure (infrastructure-to-car) [3, 4]. That will prevent traffic congestions and overall improve the traffic on highways and in big cities. Deploying of connected cars is also associated with a reduction in fuel consumption and therefore a reduction of fossil fuel emissions [5].

## 1.1 Motivation

The idea for this thesis came naturally as a continuation of our project at the Department of Control Engineering [6]. The research was supported by Toyota Motor Engineering and Manufacturing Europe as a part of Toyota Research Lab[2] Toyota Research Lab is a network of top European workplaces in the area of autonomous driving (University of Cambridge, ETH Zürich, KU Leuven, Max-Planck Institut Saarbruecken, Czech Technical University in Prague). The cooperation with Toyota started already in 2003 thanks to prof. Ing. Jiří Matas, Ph.D from Center for Machine Perception. In 2018, the cooperation of the prof. Matas' team and Toyota expanded even further.

The goal of the project was to develop and test a 1:5 RC platform (see Fig. 1.1). The

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[1] See the website http://sds.felk.cvut.cz/ for more information.

[2] See the website https://www.trace-lab.com/ for more information.

(a) Interior (b) Exterior

Fig. 1.1: Experimental 1:5 RC platform created during a faculty project. Source: Michal Bahník, 2020

created platform is built around commercially available RC car model Losi Desert Buggy. On top of the platform, there is mounted ZED stereo camera for collecting images of the surface in front of the car. The camera is also able to make depth maps and perform motion tracking together with 3D mapping. The platform contains two computers. The central unit is Nvidia Jetson Xavier with a powerful GPU which is responsible for gathering image data from the camera, data from the second computer Raspberry Pi3 with shield Navio2, and reference signals from the RC receiver. Navio2 is a board with its own ARM CPU for processing data from IMU and GPS units. The platform is used for developing and testing of various control systems.

The interest in dynamic driving at CTU FEE has been present for several years. In the master's thesis [7], the author explores laterally unstable vehicles and their stabilization by the active steering system. The thesis [8] aims to trajectory tracking of autonomous vehicles with a predictive controller. Last but not least, in [9], the author created a 1:10 RC platform for validating control algorithms. The reason for making the larger platform was to get closer to the real car's behavior and also insufficient computing power required for image processing and neural network operation. In 2020, at the time of writing this thesis, the student team eForce[3] from CTU FEE is developing the first autonomous vehicle for international races of self-driving formulas. The competitions will take place in the Czech Republic, Germany, and Spain in the summer. We have agreed on mutual cooperation on the formula project and the RC platform project. The results of this thesis may be used as inspiration or a starting point of developing the autonomous formula controllers.

## 1.2 Problem definition

The main output of the thesis is to develop longitudinal and lateral controllers for an autonomous racing vehicle. Our interest is to improve behavior of such a vehicle for fast

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[3] See the website https://eforce :cvut :cz/en/ for more information.

Fig. 1.2: Simplified autonomous car architecture. Longitudinal and lateral controllers are scope of this work. This design assumes simplification in form of decoupled longitudinal and lateral dynamics.

dynamic racing given a reference path. Dynamics of every vehicle change significantly with parameters such as weight distribution, or vehicle states such as velocity. Fig. 1.2 shows a simplified self-driving car architecture which is the same as a scheme of any mobile robot. Sensor measurements and the reference path enter both blocks with controllers. Sensor measurements consist of data from a stereo camera, IMU, and GPS. Based on this information, the car is supposed to follow the path while minimizing defined errors, for example, a perpendicular distance between the path and the center of the vehicle.

## 1.3 Outline

This work is organized as follows. After the objectives, it continues with an introductory chapter to self-driving cars (Chapter 3). This chapter provides a background of autonomous technology in terms of history, classification, and legislation. Information about autonomous racing is also presented there. The next two chapters are devoted to technical aspects of autonomous driving — mathematical modeling of vehicle dynamics (Chapter 4) and algorithms for vehicle control, together with methods for reference speed generation (Chapter 5). Vehicle control is discussed for both longitudinal and lateral dynamics. Chapter 6 describes our proposed solution for trajectory tracking of an autonomous vehicle. The last chapter before results and conclusions (Chapter 7) shows experiments made for the verification of employed control laws under different conditions.

# 2 Objectives

The thesis consists of several tasks which are listed below:

Get familiar with existing longitudinal control solutions (like ABS, ESC). Implement simulation models implementing selected functionalities.

Get familiar with existing lateral control algorithms. Implement simulation models implementing selected functionalities.

Implement the simulation framework, based on either available tools (e.g. the new Automotive Toolbox and Autonomous Driving Toolbox for MATLAB) or your own custom-built MATLAB/Simulink solutions.

Validate the developed functionalities experimentally on a subscale vehicle (modified and implemented RC car).

# 3 Self-driving Cars

The chapter introducing self-driving cars is divided into five sections that are focused on individual aspects of these types of vehicles. In the thesis, there are several designations for cars without a driver or for cars with driver and control system cooperation. We do not distinguish among self-driving, autonomous, and driverless cars/vehicles. There are many summary publications on the topic of autonomous driving. An overview of energy, environmental, and sustainability implications is given in [10]. The new book [11] presents comprehensively legal, technical, societal, and political impacts of road vehicle automation. Many surveys have been done on a technical aspect of automated driving, e.g. [12, 13].

## 3.1 History

The era of driverless cars began almost a hundred years ago. Francis P. Houdina developed the first car without a driver in 1925. It was a radio-operated automobile Chandler with a receiving antenna on the back of the car (see Fig. 3.1). The other car with a transmitting antenna had to follow the first car as shown in the image. At that time, radio signals reached only a few meters. The signals were driving small electric motors via analog components [14]. Automated guided cars were exhibited at the World's Fair in 1939. The vehicles were navigated via electromagnetic fields from coils built into the road [15].

The first promising experiments with real driverless cars began in the 1950s. In 1953, RCA Labs managed to build a small car that followed a pattern on the floor without outside intervention. Since then, there was no need to drive autonomous vehicles remotely. This company went further in development, and in 1957, they presented a full-size self-driving car. The demonstration took place on a 120-meter stretch of highway in Nebraska, US. In the same period, General Motors developed Firebirds, experimental cars described as electronic guide system that can rush it over an automatic highway while the driver relaxes [16].

In the early 1960s, the installation of automatic roads was first considered. Authorities began to see the potential of automated driving systems. Research laboratories around the world started to develop their solutions for autonomous driving, which at that time were based on the principle of guiding via electromagnetic interaction with the road (Ohio State University, Bendix Corporation, Citroën) [15]. In addition to technical research, semantic modeling techniques developed for a deductive question-answering system has also been studied since 1970 (intelligent automated logic) [17].

The 1980s and 1990s were revolutionary years for autonomous driving. Not only computing power reached a sufficient value, but also all types of commercial sensors have been developed since then (LiDAR, camera). Notable projects from the 1980s are the Mercedes-Benz robotic van capable of driving on empty roads and DARPA-funded

(a) 1926 Chandler

(b) Tesla Model 3

Fig. 3.1: Almost hundred years of development of self-driving cars. Image (a) shows the first car without a driver and (b) is an example of a modern self-driving car.

Autonomous Land driven Vehicle (ALV) [18, 19]. ALV utilized new modern technology as LiDAR, computer vision, and autonomous robotic control developed at prestigious universities in the USA (e.g. University of Maryland and Carnegie Mellon University). Two years after the introduction of ALV, in 1985, HRL Laboratories designed the first off-road autonomous navigation on the ALV [20]. Maximal speed of the ALV was 31 km/h, on complex terrain only 3.1 km/h [15]. The first neural network used for steering a vehicle was introduced in 1989 [21]. With today's perspective, the input image resolution was only $30 \times 32$ px, and it was connected, together with a laser rangefinder, to a fully connected neural network. It was one of the first usages of a neural network in control engineering (data-driven control [22]).

In 1994, the robot vehicle VaMP by Mercedes-Benz was driving on a three-lane highway in Paris performing challenging actions such as overtaking other cars [23]. Great success was achieved in 1995, when the project NavLab drove autonomously from the East Coast to the West Coast in the US [24]. The NavLab was powered by the system called RAPLH [25]. The only information available to the system was the curvature estimation and the lateral offset of the vehicle relative to the reference lane center. However, for security reasons, only steering was controlled by the system, but throttle and brakes were human-controlled. Unlike today, research on self-driving cars in the United States was funded mainly by DARPA, the US Army, and the US Navy until 2005. National Research Council published a guide for the military use of unmanned vehicles in 2002 [26].

## 3.2 Classification

The automotive industry uses many terms that are not precisely defined, and thus confusion can arise. An example of such a designation is “autonomous”. There are individuals or companies that refer to autonomous vehicles as vehicles without a human driver, and other individuals or companies mean vehicles equipped with the Automated Driving Sys-