

Sliding Mode Control for Autonomous Vehicle

Mohan Reddy Rajanna

Supervisor:

Dr. Vicenç Puig Cayuela

Mater's thesis in
Automatic Control and Robotics

Universitat Politècnica de Catalunya
Escola Tècnica Superior d'Enginyeria Industrial de Barcelona
Spain
September, 2017



Abstract

Autonomous vehicle is one of the actively researched topic in the recent times. Autonomous driving requires multi-disciplinary such as mechanical, electronics, computer science, control etc.

In this paper two models were presented and controlled by using one of the advanced technique called sliding mode control system. The first model is called kinematic model, which uses the bicycle model as the reference and the second model is dynamic model.

The kinematic model is the one in which the motion of a vehicle is defined without considering the forces and moments that affects the motion where as the dynamic model is a one in which it considers the forces and moments that affects the motion. These two models are coupled together finally.

Sliding mode control system uses $(x, y$ and $\theta)$ as an input and generates control outputs steering angle and velocity of the vehicle. The proposed control strategy is implemented in matlab and simulink on kinematic model and dynamic model is proved analytically. Most of the vehicles can be controlled using kinematic model but the same cannot be applied for the vehicles which are at high speed.

Acknowledgments

Many people have helped me along the way. Their guidance, good humour, advice and inspiration sustained me through the months of work I'd like to thank all of them.

First and foremost, I would like to express my deep gratitude to my advisor Prof. Vicenç Puig (Professor in Automatic Control at Institut de Robòtica i Informàtica Industrial (IRI) of Universitat Politècnica de Catalunya, Spain) for his continuous and patient guidance helping me discover abilities I did not know I had, for the honest and valuable advises he gave me. This thesis would not have been possible without him.

I also want to thank Eugenio Alcalá Phd student at IRI for all the doubts I asked in my initial period of the project.

A big thanks to my parents and my brothers for their support these two years to study in Barcelona during the sweetest and headrest times. A special thanks to my flatmate Kishor, and friends back home in India it is hard to name one, since there are many.

I would like to extend my thanks to UPC for providing me to do my Master's and a special the department of 'Automatic Control and Robotics'. Of-course last but not least all the professors who thought me the courses to gain the knowledge and subjects during this masters I feel thankful for them as well.



Contents

Abstract	3
Resum	5
Índex	5
Índex de figures	8
Table of content	11
1 Introduction	13
1.1 Motivation	14
1.2 Objective	14
2 State of Art	17
3 Mathematical model	19
3.1 Kinematic Model	19
3.2 Dynamic Model	21
3.3 Terminologies	23
4 Sliding mode control	25
4.1 Kinematic Controller	26
4.2 Dynamic Controller	28
5 Simulation results	31
5.1 Trajectory tracking Results	31
5.1.1 Trajectories	32

6	Effects on Economy, Society and Environment	39
6.1	Economy	39
6.2	Society	40
6.3	Environment	40
7	Cost of the Project	43
	Conclusions	44
8	Conclusions and Future work	45
8.1	Conclusions	45
8.2	Future work	46
	Bibliography	49

List of Figures

1.1	Autonomous vehicle used by Google for testing.	13
2.1	Testing of Autonomous vehicle.	18
3.1	Kinematic Model	19
3.2	Dynamic Model	22
4.1	Sliding surface	25
4.2	Kinematic sliding mode controller diagram	27
4.3	Dynamic sliding mode controller diagram	28
5.1	Coupling of Kinematic and Dynamic Model together	32
5.2	Trajectory of the circle	33
5.3	Zoom on trajectory of the circle	33
5.4	Linear and Angular velocities	34
5.5	Longitudinal error, lateral error and orientation errors	34
5.6	Trajectory of the U-turn	35
5.7	Zoom on trajectory of the U-turn	36
5.8	Linear and angular velocities	36
5.9	Longitudinal error, lateral error and orientation errors	37

List of Tables

5.1	Control parameters	32
7.1	Project budget estimation	43



Chapter 1

Introduction

The use of vehicles keeps increasing day by day and also the lives lost in vehicle accidents is also increasing. According to [5] U.S. Department of Transportation National Highway Traffic Safety Administration 5 million crashes occurred in 2015 causing 32,166 deaths and 1,715,000 injuries in U.S. By statistics, driver error is the main reason for the road accidents so companies and organizations investing huge amount of money in driver assistant, driver-less vehicles for better vehicle safety to reduce these fatalities and controlling this kind of vehicles have been a very active field of research during the last decade.



Figure 1.1: Autonomous vehicle used by Google for testing.

Figure 1.1 has no steering wheel or pedals, instead packing GPS navigation and a stop-go button as its only means of control.

Jennifer Dang in [12] demonstrated in a report that Electronic Stability Program (ESP) can reduce fatal run-off-road crashes by as much as 36 percent for passenger cars. Nevertheless, these types of systems do not take any path information into account and focus only on vehicle stabilization. With technology advancement in Global Positioning System (GPS), mapping and by-wire technologies, future driver assistance systems can utilize path information to provide proper control actuation. Autonomous vehicles give solution for these unique problems by generating their own decisions. There is no longer a human-in-the-loop control scheme for the vehicle. The system itself must close the loop from environment feedback to low-level vehicle control.

1.1 Motivation

All the facts that mentioned in Introduction and the advantages autonomous vehicle such; time management, more productive during travelling, door to door transpiration motivates me to develop advanced autonomous vehicle. There are different models available for car: linear and non-linear, kinematic and dynamic, simple ones (bicycle-like vehicle) or much more complex. The complexity of the model does not ensure better results. Sensors are needed in order to know the states and parameters of the vehicle necessary for the design of the controller. The controller is in charge of determining the actions to be performed by the vehicle.

The design of the controller can be approached in many ways. From the perspective of building a more robust and safer mode of transport the idea of developing autonomous vehicles emerges and that is why autonomous driving systems have been actively researched. Even though there are some linear techniques available but non linear techniques are most suitable to deal with uncertainties. One of the approaches to deal with uncertainties is to use sliding mode control system.

1.2 Objective

The main aim of this thesis is to create synergies and safe interactions in Integrated controller in order to obtain both lateral stability and safe clearance of advanced autonomous driving vehicle.

The following objectives can be drawn up to realize the above-mentioned aim:



- The development of a parametric vehicle model which is based on a set of vehicle (Kinematic and Dynamic model).
- The design of the longitudinal and lateral controllers
- The integration of the longitudinal and lateral controllers with an efficient control structure in order to ensure the enhanced overall performance.
- The implementation of developed vehicle model and designed controllers in Matlab/Simulink environment.

Chapter 2

State of Art

There are several research groups which are almost achieved autonomous vehicle. For instance universities like Stanford from USA, Free university of Berlin from Germany, Griffith from Australia, Oxford from UK and many more has already started to work on their autonomous vehicle. R&D division of auto mobile companies such as Audi, Toyota, Ford, Volkswagen, Mercedes, BMW, Volvo and others are also contributing significantly.

Along with these, DARPA (Defense Advanced Research Program of America) [10] is continuously improving the autonomous cars by organising an event between the researches and universities all over the world.

Google, has started to test its autonomous vehicle in the streets of California. In 2014 Google has presented driver less cars without steering wheel and pedals and they planned to make these cars available in market by the end of 2020 [6]. In 2012 Vislab, Italy has tested their solar powered autonomous car for 13000 Km from Milan, Italy to Shanghai, China [7]. In addition to these universities and companies the below figure2.1 gives wide knowledge of how desperate and effectively working with R and D to bring them on road as quickly as possible.



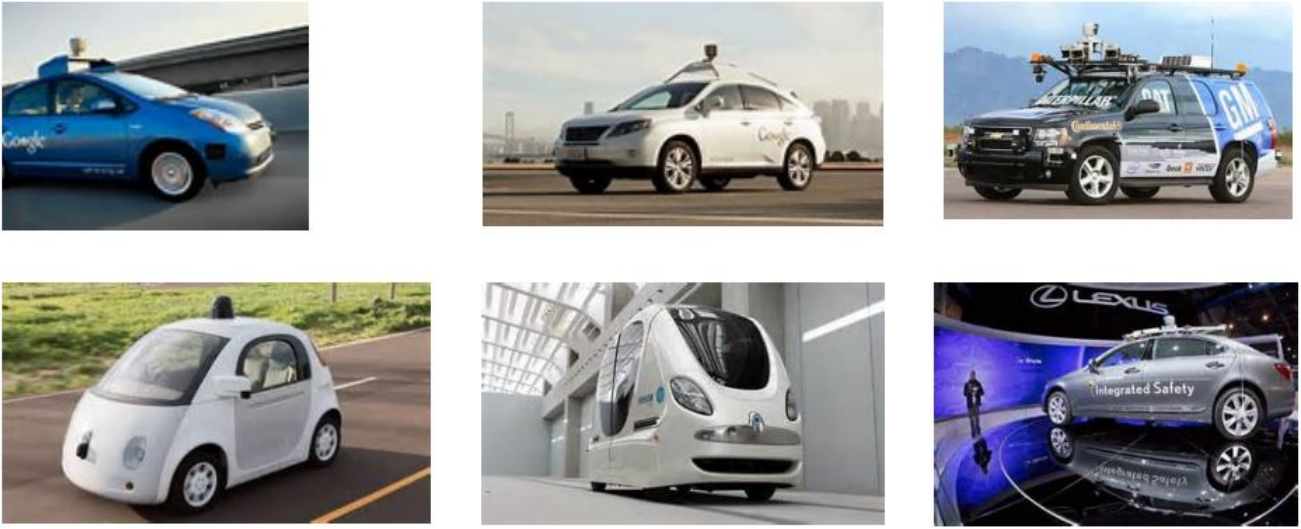


Figure 2.1: Testing of Autonomous vehicle.

Trajectory tracking control of an autonomous vehicle is one of the most difficult automation challenges due to its motion constraints: linear and angular speeds, linear and angular accelerations, etc; and there exist a constant environment interaction.

In control point of view there are several approaches discussed in literature. In practice, most of the existing systems that need to be controlled are non-linear and they have to work in different operating points. Standard linear models, known as linear time invariants (LTI), are only valid around a given operating point. The extension to several operating points lead to the LPV systems. Focusing on the difference, a clue to the main idea of LPV systems is as follows: somehow an LPV system tries to convert non-linear systems into linear parameter varying ones. LPV theory allows the use of a formulation which is very similar to the linear systems one, but it takes into account the non-linearities. For the uncertain curvature in the roads, a nested PID is used for controlling the steering in [8]. In [9] the sliding mode control technique is used to check the vehicle stability and evaluated it in simulation. There are some other literatures which are validated using higher order sliding mode control system. In addition to these MPV's (Model Predictive Control) technique is also used in trajectory tracking for autonomous vehicles and obtained robust results.

Chapter 3

Mathematical model

3.1 Kinematic Model

There are many ways to present the model, in this chapter, the model of the car is presented. The mathematical description of a vehicle in motion, without considering the forces and moments that affects the motion called kinematic model. The kinematic model of the mechanical structure of a car describes the motion with respect to a fixed reference Cartesian frame. For simplification it is necessary to state that the bicycle model simplifies the four wheel car by combining the two front wheels together and the two rear wheels together to form a two wheeled model, like a bicycle.

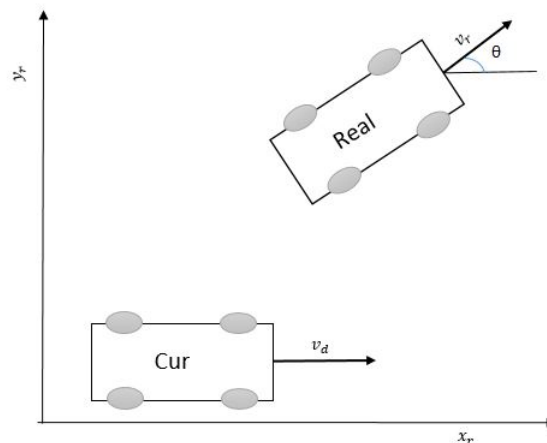


Figure 3.1: Kinematic Model

In [1], [3] it can be seen the complete development of the this kinematic model with respect to bicycle model.

The set of equations that defines kinematic model of a real vehicle in Cartesian co-ordinates(x, y and θ) are

$$\dot{x}_r = v_r \cdot \cos(\theta_r) \quad (3.1)$$

$$\dot{y}_r = v_r \cdot \sin(\theta_r) \quad (3.2)$$

$$\dot{\theta}_r = \frac{v_r}{l} \tan(\delta_r) \quad (3.3)$$

Where v is the linear velocity, δ is the steering angle, l is the distance from COG to the front wheels. Similarly the kinematic equations for the virtual vehicle can be represented as:

$$\dot{x}_d = v_d \cdot \cos(\theta_d) \quad (3.4)$$

$$\dot{y}_d = v_d \cdot \sin(\theta_d) \quad (3.5)$$

$$\dot{\theta}_d = \frac{v_d}{l} \tan(\delta_d) \quad (3.6)$$

The vehicle in world frame has three degrees of freedom(x, y and θ). The error model with respect to this can be defined as the difference between the real vehicle and the desired vehicle. From [2], the tracking error vector $[x_e, y_e, \theta_e]^T$ can be written in terms of transformation matrix.

$$\begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos\theta_d & \sin\theta_d & 0 \\ -\sin\theta_d & \cos\theta_d & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r - x_d \\ y_r - y_d \\ \theta_r - \theta_d \end{bmatrix} \quad (3.7)$$

The derivation of error vector is as follows and it will be used later to develop the control techniques.

$$\dot{x}_e = -v_d + v_r \cos(\theta_e) + y_e w_d \quad (3.8)$$

$$\dot{y}_e = v_r \sin(\theta_e) - x_e w_d \quad (3.9)$$

$$\dot{\theta}_e = \frac{v_r}{l_f} \tan(\delta_r) - \frac{v_d}{l_f} \tan(\delta_d) \quad (3.10)$$

Where w_d is the angular velocity.

3.2 Dynamic Model

Dynamic model is defined as the model by which, the motion of the vehicle which includes the forces that affects its motion. The major difference between kinematic model and dynamic model is in dynamic model, it considers the skidding. The mathematical description of a vehicle that describes the motion with respect to Cartesian frame is from [4].

$$\dot{x}_r = v_r \cdot \cos(\theta_r + \alpha_r) \quad (3.11)$$

$$\dot{y}_r = v_r \cdot \sin(\theta_r + \alpha_r) \quad (3.12)$$

$$\dot{\theta}_r = w_r \quad (3.13)$$

Where α is the slip angle. Similarly the desired dynamic model can be written as,

$$\dot{x}_d = v_d \cdot \cos(\theta_d + \alpha_d) \quad (3.14)$$

$$\dot{y}_d = v_d \cdot \sin(\theta_d + \alpha_d) \quad (3.15)$$

$$\dot{\theta}_d = w_d \quad (3.16)$$

Keeping the kinematic model as reference the error vector can be defined as,

$$\begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos(\theta_d + \alpha_d) & \sin(\theta_d + \alpha_d) & 0 \\ -\sin(\theta_d + \alpha_d) & \cos(\theta_d + \alpha_d) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r - x_d \\ y_r - y_d \\ \theta_r - \theta_d \end{bmatrix} \quad (3.17)$$

The derivation of the error vector gives the following open loop error system which will be used later to develop the control techniques:

$$\dot{x}_e = -v_d + v_r \cos(\theta_e + \alpha_e) + y_e(\dot{\theta}_d + \dot{\alpha}_d) \quad (3.18)$$

$$\dot{y}_e = v_r \sin(\theta_e + \alpha_e) - x_e(\dot{\theta}_d + \dot{\alpha}_d) \quad (3.19)$$

$$\dot{\theta}_e = (w_r - \dot{\alpha}_r) - (w_d - \dot{\alpha}_d) \quad (3.20)$$

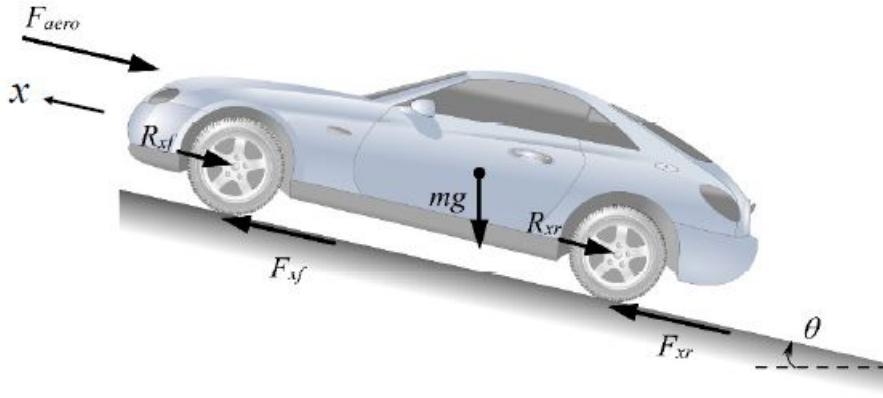


Figure 3.2: Dynamic Model

From [4], acceleration derivation of slip angle and angular acceleration is defined in terms of Force.

$$\dot{v}_d = \frac{F_{xRd}\cos(\alpha_d) + F_{yFd}\sin(\alpha_d - \delta_d) + F_{yRd}\sin(\alpha_d) - F_{drag} - F_{fric}}{m} \quad (3.21)$$

$$\dot{\alpha}_d = \frac{-F_{xRd}\sin(\alpha_d) - F_{yFd}\cos(\alpha_d - \delta_d) - F_{yRd}\cos(\alpha_d)}{mv} \quad (3.22)$$

$$\dot{w}_d = \frac{F_{yRd}\cos(\delta) + F_{yRd} \cdot b}{I} \quad (3.23)$$

Similarly these variables can also be defined in real model.

From [4], it also defines Longitudinal and Lateral forces on rear wheel and front wheel as,

$$F_{yFd} = C_x \cos(\delta_d - \alpha_d - a \frac{w_d}{v_d}) \quad (3.24)$$

$$F_{yRd} = C_x \cos(-\alpha_d + b \frac{w_d}{v_d}) \quad (3.25)$$

The aerodynamic drag force can be defined as,

$$F_{drag} = \frac{1}{2} \rho * C_D * v^2 * A \quad (3.26)$$

Frictional force can be defined as,

$$F_{fric} = \mu \cdot F \cdot g \quad (3.27)$$

3.3 Terminologies

F_{xR} is longitudinal tire force on rear tires

F_{yF} is lateral tire force at on front tires

F_{yR} is longitudinal tire force on rear tires

F_{drag} is aerodynamic drag force

F_{fric} is frictional force F is the force normal to frictional force

g is gravitational constant

μ is coefficient of the friction

a is the distance from COG to front wheel

b is the distance from COG to rear wheel

ρ is density of air

C_D is Aerodynamic drag coefficient m is the mass of the vehicle

v is the velocity of the vehicle

δ is the steering angle

α is the slip angle

C_x is the cornering stiffness

Note: The suffix d and r represents the desired vehicle and real vehicle respectively.

Chapter 4

Sliding mode control

Designing control laws that provide the desired performance to the closed-loop system in the presence of these uncertainties is a very challenging task for a control engineer. To overcome this, sliding mode control(SMC) [11] technique is introduced and it is considered as one of the most promising methods for robust control. This method uses the sliding surface or a set of them representing either a line or a curve where the system converges.

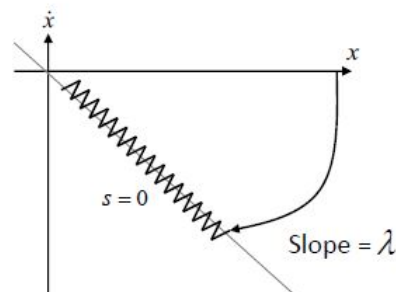


Figure 4.1: Sliding surface

One of the ways to define sliding surface for trajectory tracking control problems [?] is,

$$s(x, t) = \left(\frac{d}{dt} + \lambda\right)^{(n-1)}x \quad (4.1)$$

Where x is the tracking error and λ is a strictly positive constant which determine the closed-loop bandwidth. We can see that s depends only on the tracking error x .

Since we use second order sliding surface and we use two control actions. Therefore two sliding surfaces are used, one for longitudinal controller and other for lateral controller.

$$s_1 = \dot{x}_e + k_1 \cdot x_e \quad (4.2)$$

$$s_2 = \dot{y}_e + k_2 \cdot y_e + k_3 \cdot \theta_e \quad (4.3)$$

Where k_1, k_2 and k_3 are constants, x_e, y_e and θ_e are trajectory tracking errors and they are defined in chapter 3.

The necessary condition for the trajectory to stay within the sliding surface is $\dot{s}(x)=0$, therefore 4.2 and 4.3 will be,

$$\dot{s}_1 = \ddot{x}_e + k_1 \cdot \dot{x}_e \quad (4.4)$$

$$\dot{s}_2 = \ddot{y}_e + k_2 \cdot \dot{y}_e + k_3 \cdot \dot{\theta}_e \quad (4.5)$$

Once the sliding surface is defined, the attention is turned towards solving the reachability problem. Gao's reaching law approach Gao and Hung in [?] proposed a reaching law which directly specifies the dynamics of the switching surface by the differential equation.

$$\dot{s} = -Q \cdot s - P \cdot \text{sign}(s) \quad (4.6)$$

Where Q and P are positive constant values. By adding the proportional rate term $-Q \cdot s$, the state is forced to approach the switching manifold faster when s is large.

4.1 Kinematic Controller

In this section, a kinematic controller is designed using Sliding Mode Control(SMC)system. It considers linear velocity, angular velocity and errors as a inputs to give control outputs.

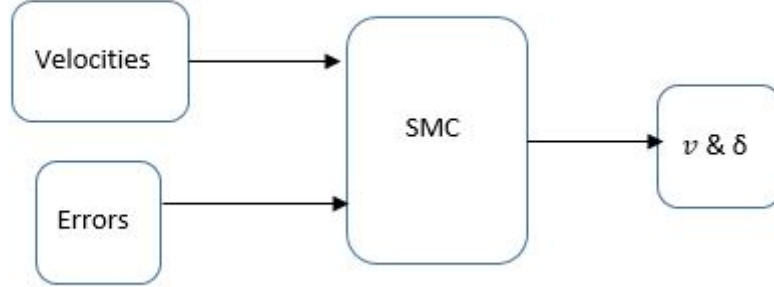


Figure 4.2: Kinematic sliding mode controller diagram

From 4.4,4.5 and 4.6,

$$\ddot{x}_e + k_1 \cdot \dot{x}_e = -Q1 \cdot s1 - P1 \cdot \text{sign}(s1) \quad (4.7)$$

$$\ddot{y}_e + k_2 \cdot \dot{y}_e + k_3 \cdot \dot{\theta}_e = -Q2 \cdot s2 - P2 \cdot \text{sign}(s2) \quad (4.8)$$

We know \dot{x}_e from 3.8 and on derivating this equation,

$$\ddot{x}_e = -\dot{v}_d + \dot{v}_r \cos(\theta_e) - v_r \sin(\theta_e) \dot{\theta}_e + \dot{y}_e w_d + y_e \dot{w}_d \quad (4.9)$$

Substituting 4.9, 3.8 in 4.14 and after some simple mathematical manipulations the following control law is obtained.

$$\dot{v}_c = \frac{1}{\cos(\theta_e)} (-Q1 \cdot s1 - P1 \cdot \text{sign}(s1) - v_r \dot{\theta}_e \sin(\theta_e) - \dot{y}_e w_d - y_e \dot{w}_d + \dot{v}_d - k1 \dot{x}_e) \quad (4.10)$$

We know \dot{y}_e from 3.9 and on derivating this equation,

$$\ddot{y}_e = \dot{v}_r \sin(\theta_e) + v_r \cos(\theta_e) \dot{\theta}_e - \dot{x}_e w_d - x_e \dot{w}_d \quad (4.11)$$

Substituting 4.11, 3.9 in 4.15 and after some simple mathematical manipulations the following control law is obtained.

$$\dot{\theta}_c = w_d + \frac{1}{v_r \sin(\theta_e) + k_3} (-Q_2 \cdot s_2 - P_2 \cdot \text{sign}(s_2) - k_2 \dot{y}_e + \dot{w}_d x_e + w_d \dot{x}_e - \dot{v}_r \sin(\theta_e)) \quad (4.12)$$

From Eq.3.10, steering angle can be defined as,

$$\delta = \tan^{-1} \left(\frac{l_f}{v_r} \dot{\theta}_c \right) \quad (4.13)$$

Where $k_1, k_2, k_3, P_1, P_2, Q_1, Q_2$ are constants and they greater than zero.

Eq.4.10 and Eq.4.12 are the control actions for kinematic SMC.

4.2 Dynamic Controller

In this section, a Dynamic controller is designed using Sliding Mode Control(SMC)system. It considers linear velocity, angular velocity, slip angle and errors as a inputs to give control outputs.

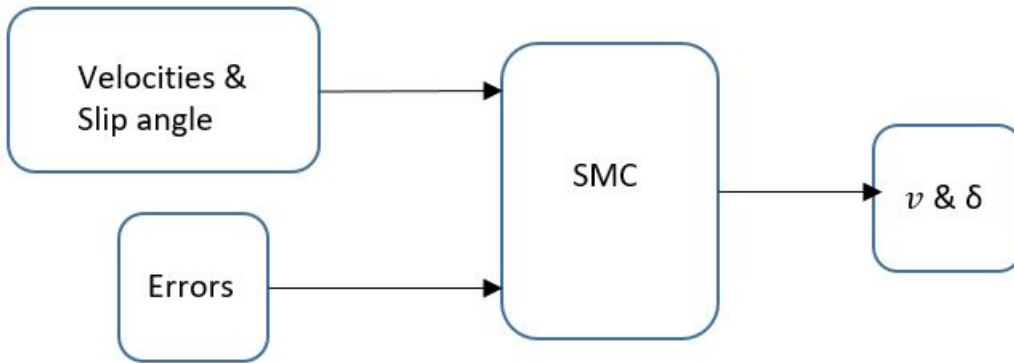


Figure 4.3: Dynamic sliding mode controller diagram

From 4.4,4.5 and 4.6,

$$\ddot{x}_e + k_1 \cdot \dot{x}_e = -Q_1 \cdot s_1 - P_1 \cdot \text{sign}(s_1) \quad (4.14)$$

$$\ddot{y}_e + k_2 \cdot \dot{y}_e + k_3(\dot{\theta}_e + \dot{\alpha}_e) = -Q2 \cdot s2 - P2 \cdot \text{sign}(s2) \quad (4.15)$$

We know \dot{x}_e from Eq.3.18 and from Eq.3.19 \dot{y}_e , after some mathematical manipulation the control actions can be achieved.

$$\dot{v}_c = \frac{1}{\cos(\theta_e + \alpha_e)}(-Q1 \cdot s1 - P1 \cdot \text{sign}(s1) - v_r \theta_e + \alpha_e \sin(\theta_e + \alpha_e) - \dot{y}_e w_d - y_e \dot{w}_d + \dot{v}_d - k1 \dot{x}_e) \quad (4.16)$$

$$\dot{\theta}_c = w_d + \frac{1}{v_r \sin(\theta_e + \alpha_e) + k3}(-Q2 \cdot s2 - P2 \cdot \text{sign}(s2) - k2 \dot{y}_e + \dot{w}_d x_e + w_d \dot{x}_e - \dot{v}_r \sin(\theta_e + \alpha_e)) \quad (4.17)$$

The above equations Eq.4.16 Eq.4.17 are the control laws for the Dynamic model.

From Eq.3.10, steering angle can be defined as,

$$\delta = \tan^{-1}\left(\frac{l_f}{v_r} \dot{\theta}_c\right) \quad (4.18)$$

Chapter 5

Simulation results

This Chapter shows the different results obtained in simulation from the application of the proposed Sliding Mode Controller (SMC) for the autonomous vehicle. A description of the Simulink scheme used for simulation is given, results are presented in an order to help the reader to understand the design procedure for Kinematic and Dynamic. Finally, two different reference trajectories: A circle and a U-turn and are tested for the kinematic SMC. Reference inputs, trajectories of the virtual and real vehicle, states, control inputs and errors between the virtual and real vehicle's output are the results of interest shown.

5.1 Trajectory tracking Results

In order to prove the performance of the control technique the trajectory set by the reference vehicle has to follow the real one. The below Figure 5.1 is a Matlab/Simulink diagram. A brief description is given on the blocks before starting the simulation results. The trajectory planner develops linear and angular velocities as first output and Longitudinal, lateral and orientation of the vehicle as a second output, this trajectory planner is also considered as reference. The error block will consider x , y and θ as an input of both reference and real vehicle model and produces the longitudinal, lateral and orientation errors by considering the equations from Eq. 3.7. The blue block is the kinematic SMC it takes errors and velocities as an input for the block to give the control outputs. It uses the equations Eq. 4.10 and Eq. 4.12. Finally the Kinematic vehicle model will generate the position and orientation for the respective control actions.

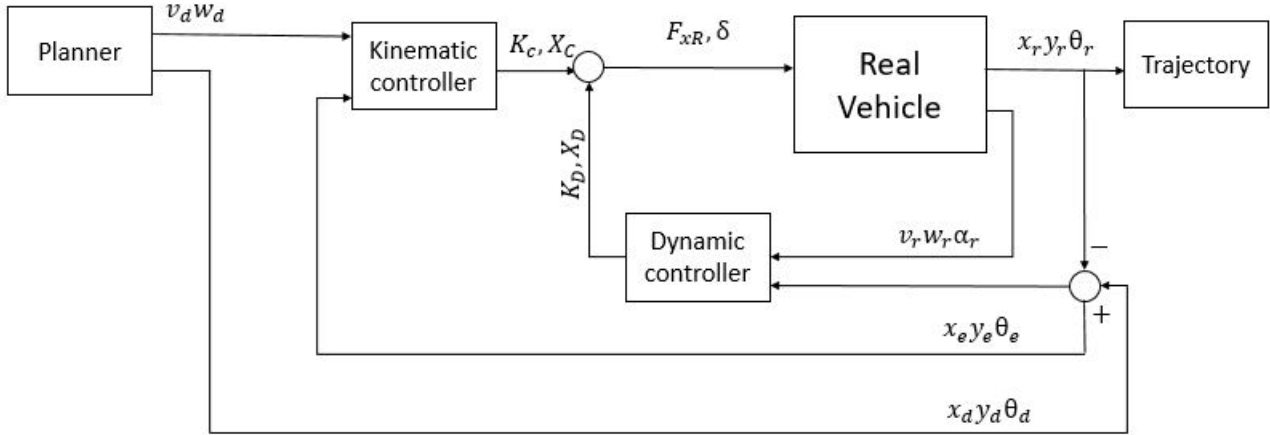


Figure 5.1: Coupling of Kinematic and Dynamic Model together

5.1.1 Trajectories

In this subsection, two different trajectories are presented and the results were disused. The following control parameters are used for both trajectories.

Constants	Value
k_1	0.22
k_2	2.5
k_3	3.183
Q_1	0.48
P_1	0.048
Q_2	3.7
P_2	0.3

Table 5.1: Control parameters

The **Circle** is obtained when the reference velocity is at $3 \frac{m}{s}$, the trajectory obtained can be seen in the below figure5.6. It can also be seen that in figure 5.7 the switching surface is fast.

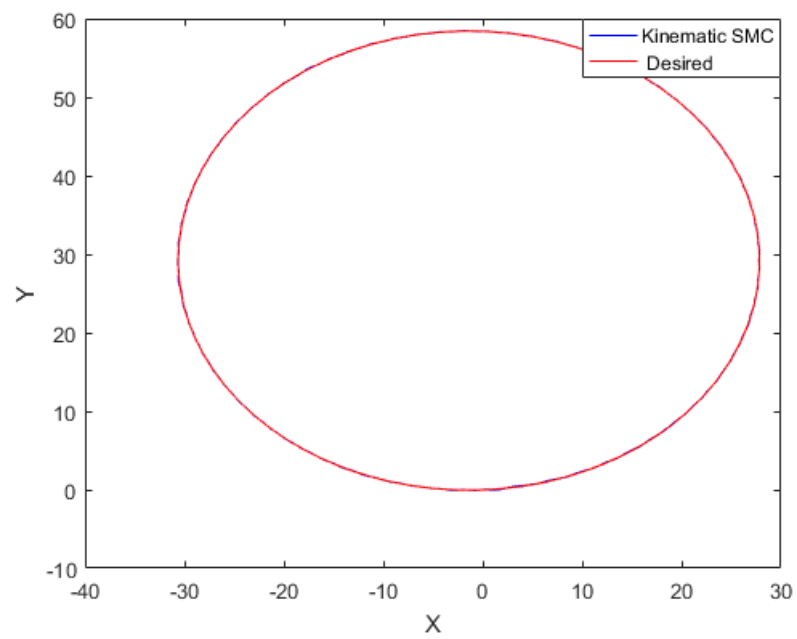


Figure 5.2: Trajectory of the circle

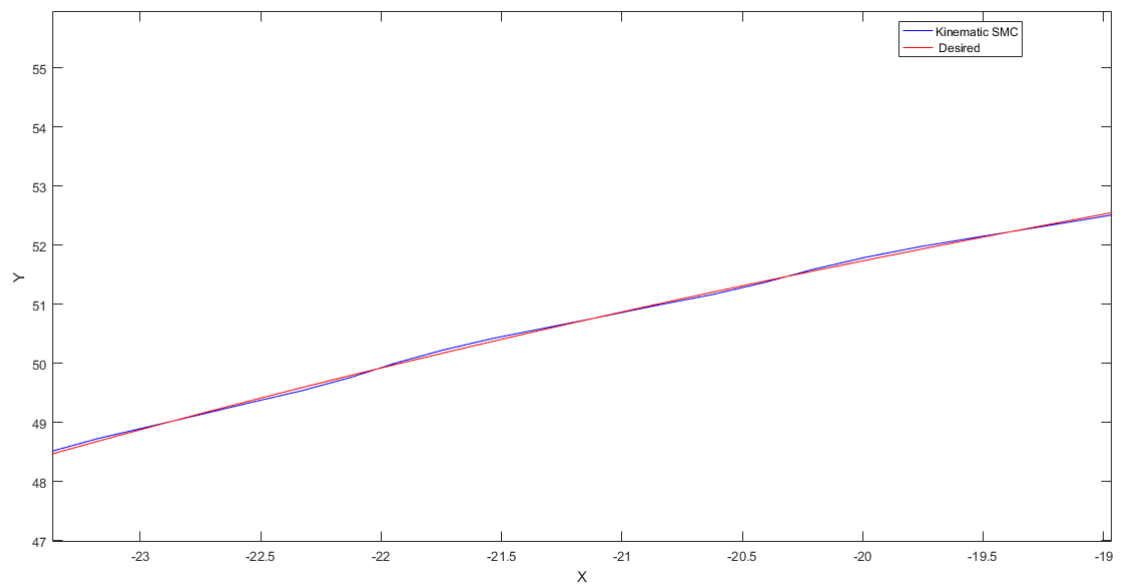


Figure 5.3: Zoom on trajectory of the circle

In the next figure, the behaviour of the linear and angular velocities can be seen. The desired velocity is fixed at 3 and it can be seen that real velocity is following the desired velocity.

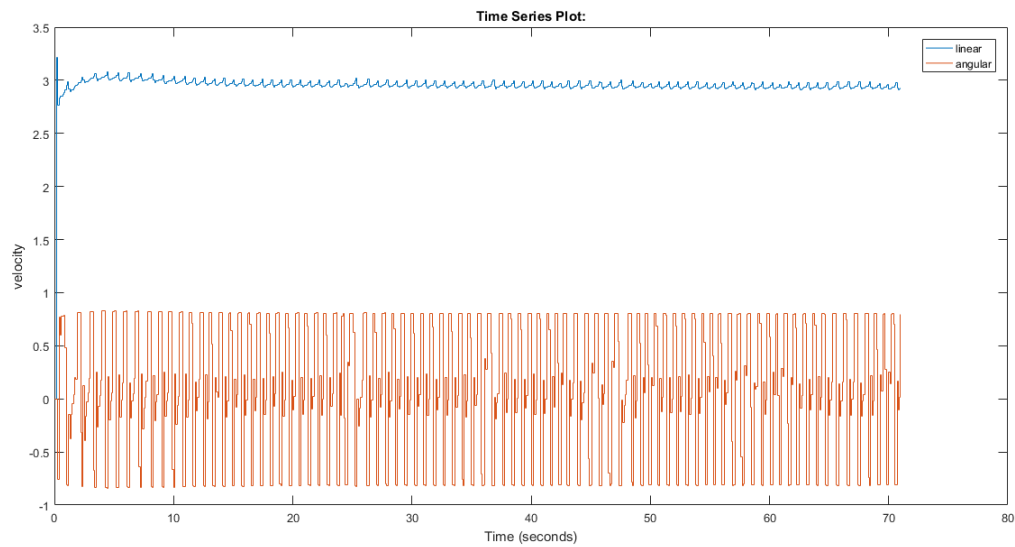


Figure 5.4: Linear and Angular velocities

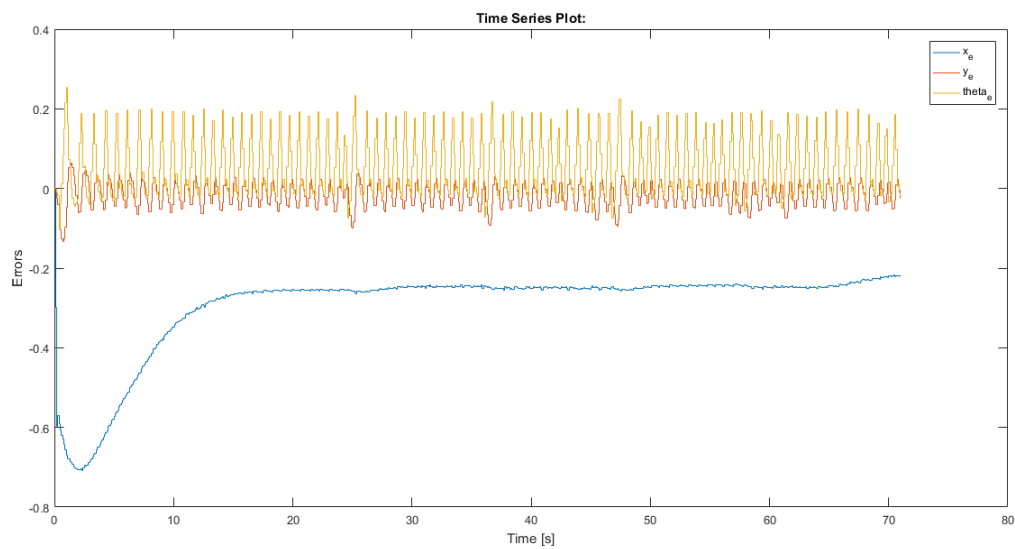


Figure 5.5: Longitudinal error, lateral error and orientation errors

As time progresses one can see that the errors are trying to minimize from the above figure5.9

U-Turn trajectory can be seen in the below figure5.6.It can also be seen that in figure 5.7 the switching surface is very slow in the curvature, the blue line is moving away from the desired path. There are some several techniques to avoid this problem.

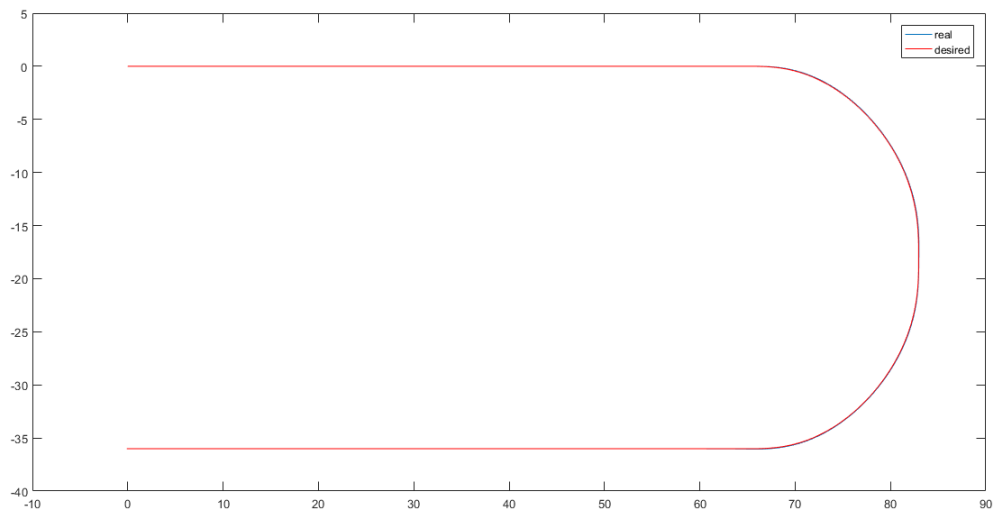


Figure 5.6: Trajectory of the U-turn

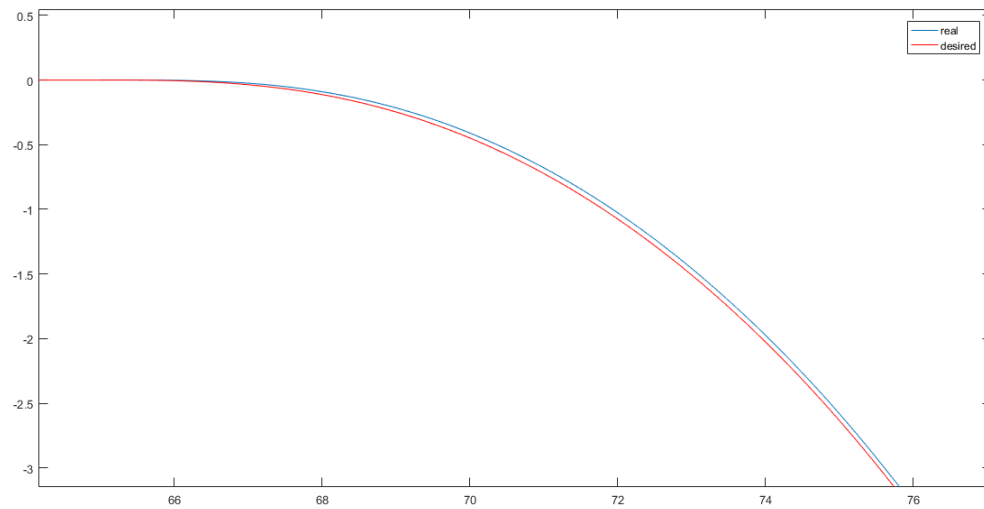


Figure 5.7: Zoom on trajectory of the U-turn

In the next figure, the behaviour of the linear and angular velocities can be seen. The desired velocity is fixed at 1.6 and the real velocity has reached quick time instance.

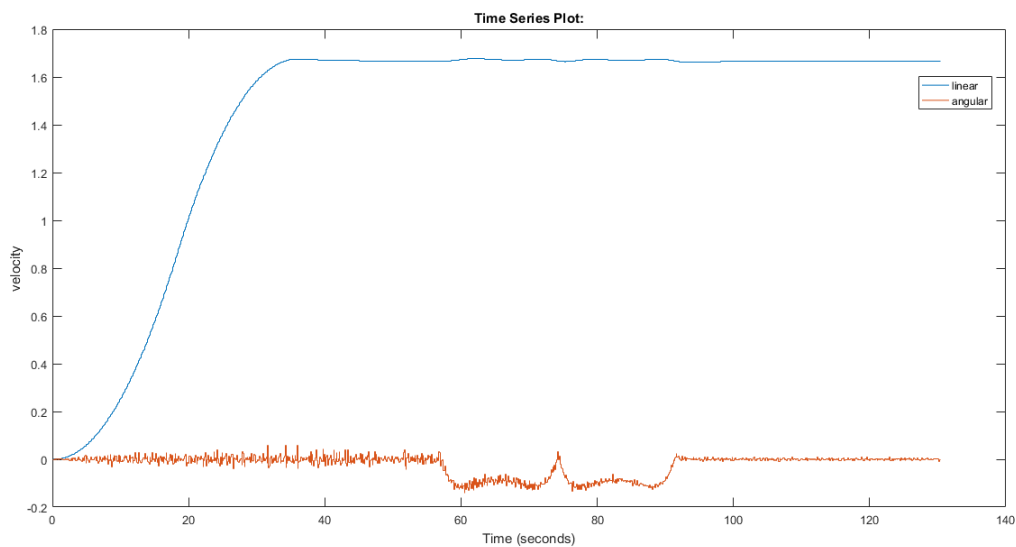


Figure 5.8: Linear and angular velocities

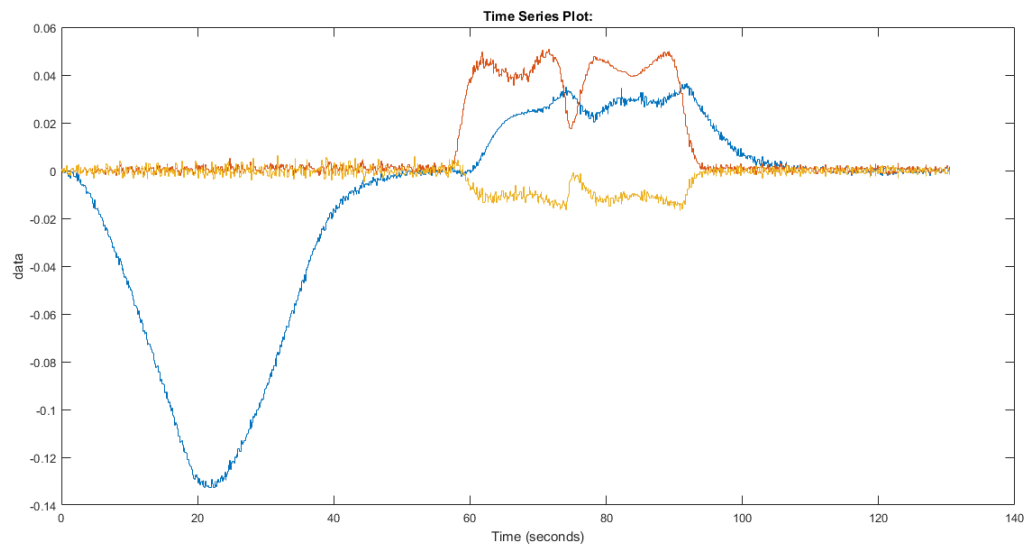


Figure 5.9: Longitudinal error, lateral error and orientation errors

The comparison of Zoom between the **Circle** and **U-turn**, it can be clearly seen that the circle trajectory tracking of the real vehicle is very good as the switching surface quickly. On the other hand U-turn trajectory tracking at the curvature is not really good, for the control parameters. So one can conclude from the above results is that depending upon the path or trajectory the control parameters should be chosen. It is also important to keep in mind the chattering effect.

Chapter 6

Effects on Economy, Society and Environment

In this section, an introduction of possible impacts on economy, society and environment are presented. Nowadays, mobility and transportation play a very important role in our society. Autonomous vehicles could be the new paradigm for it. The way it will affect us in the long run is not determined but some clues exist. It will have an impact on the environment, our society and the economy.

6.1 Economy

Vehicles have always had a huge impact on society and economy. In some countries, the vehicle production corresponds to a high percentage of its industry. Then it is important to take care of how vehicles are integrated in society.

Every life lost and injuries as a result of a traffic accident has a social but also a financial cost. The possibility of saving and having more free time due to transportation can be used, for instance, to enhance people and businesses productivity. Companies in the transportation sector have the opportunity of cutting costs by reducing the number of drivers. This would surely cause a social impact due to job losses. Another sector that should adapt to the new paradigm is the insurance one. Insurances will no longer be about writing individual insurance policies. Some investments in infrastructures might be necessary to adapt the roads to the new way of travelling. This could be costly but in the long term more efficient, hence it is difficult to predict the economic impact because the solution that will be adopted is unknown at the

moment.

6.2 Society

Many people nowadays spend a significant proportion of their time travelling and there is an increasing demand for comfort, in private and public transportation, the time spent on driving can be reduced.

All though, the main social benefit of automated driving is the possible effect that it can have on the number of deaths and injuries on road. This is a fact in our society that will hopefully change drastically as autonomous cars become widespread. The majority of traffic accidents are caused by human errors. This is the reason why the majority of the developing projects in transportation are related to safety issues.

Autonomous vehicles will open new possibilities of using and saving travelling time, instead of driving the focus can be on other matters and also the car could go to the car park by itself. There is a cultural frame around cars, freedom or status are good examples of it. This culture will evolve and change as ideas of approaching transportation vary.

It is also interesting to see the impact of autonomous vehicles to assist elderly and disabled people.

6.3 Environment

There exist many contamination types, but society is interested in two: noise and air pollution. With the introduction of electric autonomous vehicles, we will achieve a world without uncomfortable noise in the streets, not only for the fact of being electric vehicles but also for the fact that all vehicles will be interconnected and the car horn could be suppressed.

Regarding the pollution, the electric motor does not contaminate. It means a significantly reduction of the world atmospheric pollution. The idea of having a net of connected autonomous vehicles would reduce the number of vehicles in the streets, what would lead to an increment of parking space.

Until this moment all effects discussed were positive but there also exist negative impacts. One of them is that the vehicle batteries have a limited life, it means that we would have to replace them every defined period with the consequent accumulation and contamination. But the most

important point is that, manufacturing an electric vehicle generates as carbon emissions as building a conventional car due to its battery.

Chapter 7

Cost of the Project

In this chapter, we provide some considerations about the development and implementation of the control and planning system from an economic point of view. It will be considered the study of the costs as whether the system was to be introduced in the market. Although it is very difficult to give unit cost because it is hard to choose the number of vehicles produced and sold.

Description	Cost(€)
Computer	800
Vehicle	3500
Matlab License	2000
Simulink License	3000
Total Assets	9300
Salary	15000
Overhead costs	1000
Other Costs	1000
Total Cost	26300

Table 7.1: Project budget estimation

The table above gives the overall budget implementation of the project that was used for its de-development.

To run the algorithm, a master computer is required since the Dynamic model and controller has complex equations. It is assumed that an average masters student at his beginning of his career can approximately get his salary 30000 per annum, we choose 15000 because this master thesis carried out and finished in six months. Other costs includes, travel expenses, energy used, paper, food, etc., which is approximately estimated during the project. There might be another

costs like office-rent, parking for autonomous vehicle etc., but they are neglected because my work base is home and university. In the end the total budget for this project is 26300. This new control system on vehicle would have major impact on vehicle price and makes profit on it.

Chapter 8

Conclusions and Future work

In this work, we have dealt with the autonomous driving problem from the planning and control point of view. We have studied the equations that govern the vehicle behaviour presenting three different models namely kinematic, dynamic and combining them together.

This thesis describes trajectory-tracking and path-following controllers based on the sliding-mode theory for autonomous vehicles. The Sliding Mode Control technique that is based on deriving a controller that forces system dynamics to reach the sliding surface and remaining there what ensures a null error. The proposed control structure is based on two non-linear sliding surfaces ensuring the tracking of the three output variables. The control law has been thoroughly evaluated in terms of tracking performance either by simulation and real experiments.

8.1 Conclusions

Some remarks are made based on this thesis,

- Simulations are very useful to test the results before they implement in the real vehicle. Matlab/Simulink is a powerful tool to test these kind of tracking control problems.
- From the experiment results, it can be conclude that, it yields better results in constant velocities than that of variable speeds.
- Almost all the vehicles can be controlled with simple kinematic model, without using the complexity of the dynamic model. On the other hand it is also important to consider

that with the simple kinematic model, the vehicle can operate only at low speeds.

- It can also conclude that, it is suitable for lower velocities, for higher velocities need to include slip angle and hence the complexity of the system is also increases.
- The SMC control law adjusts to its results because it has seven parameters to tune. However, in Unity SMC law has achieved a higher performance obtaining a lower percentage of error a long the test. So, it can be concluded this control method is robust, it just depends on one vehicle parameter complexity to adjust but it obtains very good results when is properly adjusted
- There exists a chattering problem in Sliding Mode Control system and a proper tuning and sliding surface is necessary for to yield better results.

8.2 Future work

In regards to future work, the focus will be on improvement of current work and development of system with new functions and technologies. The following suggestions are recommended:

- It would be interesting to study the sliding-mode control design using dynamical model alone, where uncertainties in the robot physical parameters exist.
- Further investigation is necessary on the details of weight distribution on tire forces and moments for vehicle stability control especially in cornering situations
- Future work will include further investigation into increasing the robustness of the integrated controller. Strategy tuning, control threshold value tuning, real-time implementation of integrated controller and experimental verification for different road conditions, are the future areas of research to extend the applicability of the proposed control method.
- The performances of the four reaching laws can be compared in order to establish an on-line parameters adjusting procedure and deserves more study.
- It is also interesting to see other control technique apart from Sliding Mode Control system on Dynamic model.

The topic of nonlinear control systems is large and receives a lot of research interest in both journals and conferences. This thesis has touched aspects with relevance to controller design, robotics and in particular mobile robotics. Questions have been answered, new ones have appeared. With the appearance of smarter sensors, faster computers, and more reliable data processing, the design and implementation of nonlinear control techniques for mobile robotics are of great interest and should attract further investigations.

Bibliography

- [1] Gao, W. and Hung, J. C. Variable Structure Control of Nonlinear Systems *IEEE Transaction on Industrial Electronics*, 40(1) 45-55., 1993.
- [2] Alexandru Stancu, Eduard Codres and Vicenç Pui. *A Fault Hiding Approach for the Sliding Mode Fault-tolerant Control of a Non-holonomic Mobile Robot*
- [3] Snider, J.M. *Automatic Steering Methods for Autonomous Automobile Path Tracking*, 2009.
- [4] Rajesh Rajamani. *Vehicle Dynamics and Control*, Second Edition, Springer. Chapter 2 and 4, 2012
- [5] U.S. Department of Transportation National Highway Traffic Safety Administration. *Traffic Safety Facts 2009*, A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System, 2015.
- [6] Halleck, T. Google inc. says self-driving car will be ready by 2020. *International Business Times*, 2015
- [7] Bianco, C. G. L., Piazzzi, A., and Ramono, M. Velocity planning for autonomous vehicles *IEEE Intelligent Vehicles Symposium*, (2004).
- [8] Marino, R., Scalzi, S., and Netto, M. A nested pid steering control for lane keeping in vision based autonomous vehicles. *Control Engineering Practice*, vol 19 (2011), 1459-1467.
- [9] Solea, R., and Nunes, U. Trajectory planning and sliding-mode control based trajectory tracking for cybercars. *Integrated Computer-Aided Engineering*, vol 14 (2007), 33-47.
- [10] Levinson, J., Becker, J. A. J., Dolson, J., Held, D., Kammel, S., Kolter, J. Z., Langer, D., Pink, O., Pratt, V., Sokolsky, M., Stanek, G., Stavens, D., Teichman, A., Werling, M., and Thrun, S. Towards fully autonomous driving: Systems and algorithms.

- [11] E.Slotine, J.-J., and Weiping Li. *Applied nonlinear control*.
- [12] Jennifer N. Dang. Statistical analysis of the effectiveness of electronic stability control (esc) systems, *Applied nonlinear control*. , July 2007.