Chapter 1

Introduction

The dawn of autonomous driving has brought new challenges to existing vehicle systems. In fact, from 1986 to 1995 the PROMETHEUS project was one of the first to tackle the challenge by bringing new intelligence to control the steering, gas and brakes[2]. Of these three systems, it is the steering system that is primarily responsible for the vehicle lateral dynamics. In this respect, the steering system remains crucial to the success of autonomous driving as it is the primary system to control the vehicle through bends. Indeed, over the last decades more intelligence has been added to the system for both driver assistance, automation, as well as, functional safety. This work focuses on the automation of the steering system within the scope of developing self-driving vehicles.

The historical development of the steering system can be broken down into two related areas. Firstly, the underlying technology or hardware-layout; secondly, greater functionality through software. For example, the hydraulic rack assistance layout was commonplace for most vehicle types up until the end of the 1990s. Today, however, a mix of column and rack base electro-mechanical power steering (EPS) layouts are almost universal. Along side the changes in hardware, additional functionality has been implemented onto the steering electronic control unit (ECU). Indeed, since the power assist steering was first introduced onto the market in 1951 [25], the steering system has continuously improved in functionality. One of the recent widespread development in this regards has been the addition of Advanced Driver Assistance Systems (ADAS).

For the most part, the improved steering functionality, including ADAS, has focused on the driver playing a pivotal role in controlling of the vehicle. Autonomous driving, on the other hand, demands a rethink of the steering system functionality. No longer is the driver the central controller of the steering system, rather, the onboard autonomous system commandeers the steering to follow a designated path. Moreover, the role of the driver in this system changes based on the level of autonomy.

Figure 1.1 shows the various levels of automated driving based on the German BASt definitions [69]. The definitions of ”driver only” and ”drive assistance” have been removed for brevity as these do not follow the criterion that the autonomous system is the central commander of the steering control.

The description of the levels as it pertains to the steering system are given as follows:

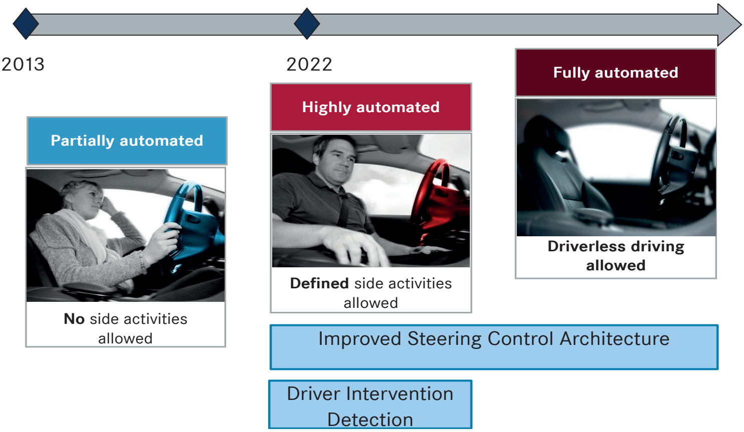

Figure 1.1: Autonomous driving levels. Pictures from Mercedes-Benz AG

Partially automated: The automated driving system controls the steering under very specific circumstances, e.g. highway driving. The driver must constantly observe the driving situation. This test for observation can be achieved by detecting the driver's hands guiding the steering wheel.

Highly automated: The system completely controls the steering. This may also be under specific driving situations. The driver, however, can now perform side task and may ignore the driving situation. When the system is outside the normal operating condition, an alert will be given to the driver to take-over the driving tasks. The driver can also take-over the driving at any point he feels the desire to.

Fully automated: The system controls the steering under all driving conditions. There may or may not be a driver in the vehicle. The system is fully capable of safely commandeering the vehicle even in a degraded state. In some vehicle concepts the driver may have the ability to take over the driving task if he so desires.

As of 2022 the area of partial automation is mostly widespread in systems like Mercedes's Distronic Plus® with active steering assist or Tesla's Autopilot. Currently the Mercedes Benz S-Class is the first and only vehicle to have received international approval for highly automated driving [3], however, this is currently under extremely limited conditions of highway driving below 60 km/h. Finally, a fully automated driving system is still a number of years away.

This work focuses on highly automated driving, for which a significant development challenge remains, namely its expansion to work under most driving conditions. Additionally, this work contains valid aspects for fully automated driving.

1.1 Role of Electric Power Steering (EPS) in Autonomous Driving

As mentioned above EPS is the most adopted steering technology in vehicles today and is the basis for autonomous driving steering control. In particular, the steering system that is currently being focused on, is the parallel axis steering gear layout shown in Figure 1.2.

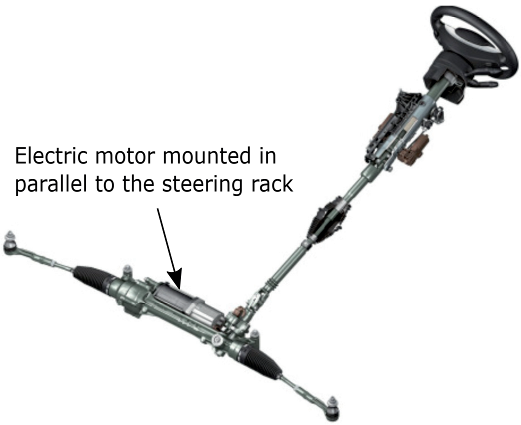

Figure 1.2: EPS Parallel axis system from a Mercedes SL (2012) [1].

This layout is the common choice for luxury and high-end vehicles due to its relatively low friction and high efficiency to meet the high load demands [55]. This is currently also the universal steering layout for autonomous driving due to the price point of the vehicles attempting to achieve the level of high automation.

The use of the EPS during both manual and autonomous driving is explained in the control scheme shown in Figure 1.3.

First, in its conventional form the EPS is used as a non-linear amplifier. This means that the driver's hand torque is used to generate an assist torque from the electric motor. This assist torque is a function built up in software by the so called steering feel modules. Additional inputs like steering wheel angle and speed, as well as, the vehicle speed are used to determine the amount of assistance torque the driver experiences, thereby influencing the drivers steering feel during cornering.

Second, Figure 1.3 also shows a possible architecture during autonomous driving. Here, the environment recognition function generates a desired trajectory, which is sent to the lateral dynamics controller to be followed. The lateral controller inturn sends out a desired front steer angle to be tracked by the steering position controller. The vehicle drives a path, which is fed-back to the trajectory generation to close the outer loop. This type of cascaded control structure is commonplace in the implementation of a path following vehicle system. It has been noticed that when both the manual driver assistance and autonomous paths are active during partially automated driving, the assistance modules negatively interact with the required torque from the autonomous path. This unwanted effect is known as "cannibalisation". Having only one of the paths active at a time, requires the design of a take-over mechanism which would allow the driver the chance to take back control of the vehicle at specific instances. This architecture is inline with the definition of highly and fully automated driving given previously.

The area of focus for this work, indicated by the green block in Figure 1.3, is the development of the underlying steering angle controller and take-over mechanism.

An alternate technology of steer-by-wire systems has been around from the 1990s. These systems are particularly advantageous to the problem of driverless steering control due to the decoupled steering wheel. However, the early 2000s have mostly seen a stop in the development of these systems in commercial vehicle manufactures. Consideration of other by-wire systems, points at brake-by-wire developed by Bosch and Mercedes Benz. But these systems have not, as yet, been established in the market. Safety issues involved are not completely addressed and are undergoing further research [46][29]. In this regard, the driver currently remains a central point in vehicle control, hence the future would require coexistence rather than a replacement of the conventional parallel axis system.

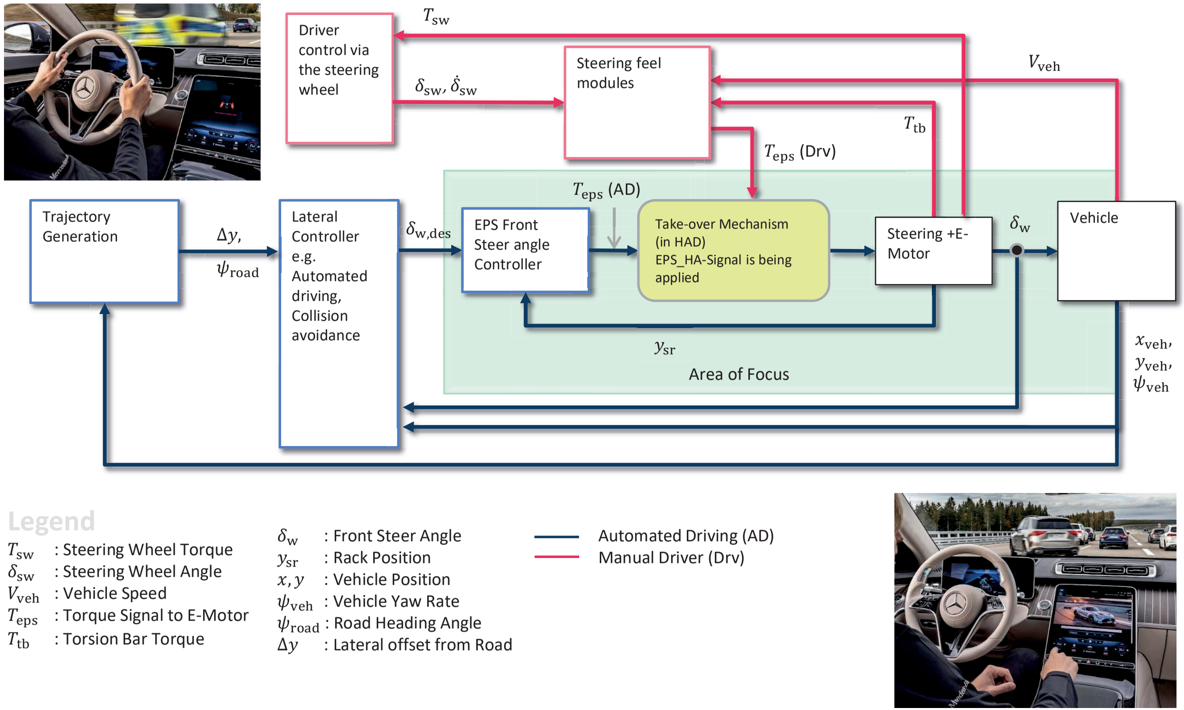

Figure 1.3: This figure shows the system's architectural paths for manual and autonomous driving

1.2 Related Works

1.2.1 Driver feel

Over the last decades research on steering control was heavily focused on the ability to transfer steering feel to the driver. Initially, numerous works dealt with the hydraulic (HPS) or electro-mechanical (EPS) system with a steering column attached to the rack [24][56][42][43][68][14][75]. The central idea revolved around creating a desired driver's hand torque based on various driving situations. While, driver feel is not within the scope of this work, a few relevant aspects to the problem of automated control will be mentioned in the context of the follow steering system layouts.

Driver feel in Hydraulic Power Steering (HPS)

For hydraulic systems an additional control device such as described in [56] allowed the level of hydraulic assistance to be altered, thereby changing the driver's hand torque. Additionally, in [24] it was not only attempted to generate a desired hand torque but estimate and compensate unwanted road frequency without effecting the road feedback. Various model-based approaches were used in this area of control. The works of hydraulic systems require detailed modelling of the valve and hydraulic behaviour, therefore, this legacy system offers limited related work to the task proposed above. For trucks, however, hydraulic power steering is still a current technology which couples hydraulic and electric power steering.

Driver feel in Electric Power Steering (EPS)

Works by [15][39][44][26][43][52] are a few selected studies examining the control of the EPS to generate both a steering wheel torque, as well as, compensate for unwanted vibrations. The dissertation [14] models a parallel axis steering system using a multi-mass oscillating system. The models were developed directly in the linear system domain thereafter the parameters were identified. To improve modelling accuracy, Coulomb friction was considered as a hyperbolic tangent function added to Stribeck friction. The control focus was on the torsion bar torque and an $H\infty$ scheme was the preferred controller chosen. Mehrabi [44] and Shi [52] both use an LQG based scheme on a column type EPS to control the driver torque. By manipulating the traditional characteristics curves (Boost curves) [26] presents an alternative to direct control of the torsion bar torque. In this work the motor current is the control value which is controlled using a PID controller. The desired current is created using a series of look-up tables mapping the system input dynamics to a current setpoint. Work shown in [43] extends the idea of direct motor control by using the the rotor angle as a subordinate control loop and the desired torque generated from boost curves on the outer loop. A model-based sliding mode control is also derived from the linear description of the column steering system, including a bicycle model to build up the self-aligning torque at the wheels. Of particular interest with the direct motor control was the modelling and the compensation of the cogging phenomenon for EPS motors described in [34]. Here the author models cogging based on the motor's physical structure delivering a primary harmonic. Additionally, [20] presents this primary cogging torque in a Fourier expansion and uses a feedforward scheme to compensate for it.

Driver feel in Steer-by-wire (SbW)

Steer-by-wire systems inherently have the task of controlling the driver's hand torque. In fact, the decoupling of the rack and steering column allows greater design freedom for the driver feedback. Work by [17] presents a modular steering torque computation. The author mentions that the rack force is a key component of delivering hand torque which represents the vehicle road interface. Work from [67] offers a way to estimate this using a linear disturbance observer on a single mass model of the steering system. Work presented in [59] developed a hydraulic fallback solution for SbW which recreates an EPS hand-torque. Once again, the focus was the control of the driver's hand-torque in the fallback situation. A critical aspect of the accuracy of these approaches is the non-linear modelling of friction. In this regard, the LuGre model was used and will be mentioned in Section 1.2.3. Further work by [41] extends on the friction compensation by using an adaptive parameter approach using an dual observer for the bristles in the LuGre model.

1.2.2 Front steer position control

The more central area of work for this dissertation is in front steer position control. One of the early works in this field is from [70]. Here an electro-hydraulic steering system is fitted with a special valve to actuate the system. The goal was to create an accurate steering controller within a front angle of $\pm$ 15° for agricultural purposes for speeds under 20 km/h. An adaptive PID scheme with a feedforward action was developed. The PID controller uses an adaptive turner taking information from a Kalman filter, which estimated the disturbances on the system. For the EPS there are only few works, for example [64] and [31], that focus directly on this topic. In [64], the author presents a cooperative control scheme which allows for some parallel driver input during path following. This is contrary to the architectural scheme presented in Figure 1.3, which will be used as a basis for this work. Moreover, the front steer control performance was not focused upon. As such, the issues of steering wheel oscillations at higher dynamics are not dealt with. The underlining steering position control proposal fits many state of the art industrial control strategies. A cascaded control structure contains a PD outer loop in parallel with a first order feedforward action, however, instead of the inner loop controlling the steering velocity, a disturbance observer is used to compensate for unmodelled effect to create a zero steady state offset. Additionally, the scheme presents noise and disturbance effects on the front steer velocity in the framework of a first order transfer function. The scheme is controlled using 4 parameters, namely, two for the PD outer loop, the feedforward gain and a factor to shift the steady state tracking stiffness.[65]. A broadly similar scheme will be benchmarked in this work.

In [31], a scheme for steering angle control with an EPS System is presented. Firstly, the steering system from motor torque to rack is modelled as a 2^{nd} order system. The steering column is, however, neglected. This simplification is therefore relevant for steer-by-wire systems, but does not deal with the complexity of including the column, which is an additional oscillating mass. The controller presented is a simple PI scheme shown in the form of an internal model control (IMC). This is perhaps suitable for a steer-by-wire scheme, however, not a traditional EPS layout with the performance demands for autonomous driving [21].

In fact, there are a number of works such as those in from [71],[74][47] which adopt some form of PID control to move the rack to a desired front steer angle. In the dissertation [18], the author suggests that for the problem of accurate position control for steer-by-wire systems, classical control methods applied to a lower order plant model are sufficient. Indeed, the performance specifications presented in [18] indicate that a 4 Hz control bandwidth was reached using such control and is adequate to recreate the full range of steering behaviour under all driving conditions. This conclusion can be entirely explained due to the simplification of the steering rack control problem for steer-by-wire systems. The decoupling of the oscillating mass, i.e. the steering column in an EPS system, reduces the problem to a single mass system with the cornering tyre forces treated in the most cases as a disturbance.

1.2.3 Frictional Effects within the EPS system

As explained in the above sections, the modelling and compensation of friction plays an important part especially for steering feel in both EPS and steer-by-wire systems. However, steering position control has been relatively under-researched concerning the benefit of an explicit friction compensation. In [64], friction is modelled and compensated during front steer angle control, however, the improvement using the compensation in addition to the designed control structure is not shown. Nonetheless, it is commonly accepted that the modelling of an EPS system requires an accurate modelling of the friction effects. In this regards, a number of friction models of varied degree of complexity have been used. In recent times, a bristle type friction called the LuGre Model [50] has been adopted for steering system modelling. The advantages of this type of modelling is in the reproduction of hysteresis in the sticking phase as well as continuity, which is important for control. In [4], the benefit of the LuGre model in conjunction with slow moving mechanical control applications is shown. Furthermore, a number of the works, e.g. [68], have shown a good reproduction of friction phenomena with this modelling for the use in the areas of steering feel and positional control. In [67], the frictional effects on a loaded steering system are examined and a modification of the static friction for speed and load is proposed. Nonetheless, its model structure, as explained in Appendix B, is relatively complex. Works from [11], [66] and [63] suggest the use of the Dahl and Masing model offer comparable accuracy without the additional complexity of the LuGre Model.

1.3 Goal of this thesis

This work is aimed at the investigation and design of an effective front steer position control scheme for the levels of autonomous driving shown in Figure 1.1. The target steering system hardware for this work is a parallel axle steering gear with a fixed steering column to attach the steering wheel. It takes the architecture presented in Figure 1.3 as a starting premise. This allows the controller performance to be demonstrated without any unwanted negative effects from the driver feel modules, while still permitting the driver the ability to regain control of the system.

A secondary aim of this work is to use a deep understanding of the system to inform the design choices for the controller. This system analysis involves the creation of suitable reference and plant models both for the control synthesis, as well as, for the reference performance. Additionally, the friction of the EPS system is thoroughly investigated, with the aim of demonstrating the usefulness of friction compensation within the control scheme. A steering control performance specification to fulfil the requirements under all driving conditions for autonomous driving will be developed for the control design goals. Section 1.2.2 presented a few state of the art control structures used to tackle the problem of partial autonomous driving. An investigation into their structural drawbacks will be conducted. This is done with the focus on their ability to meet the performance criteria. In order to prove that the controller developed within this work meets the performance criteria in real-world conditions, a comprehensive validation within a representative vehicle was also undertaken.

Finally, a suitable take-over mechanism for manual driving will be developed.

In order to aid these goals a steering gear with an open desired torque interface was available. Moreover, at Mercedes Benz AG a steering test bench and test vehicle with the controllable steering gear was set-up.

The overall goals of this work can be listed as follow:

- System analysis with a view to control the steering system.
- Develop a reference and synthesis model of the steering system
- Design a front steer position controller
- Controller validation
- Hands-on detection

1.4 Structure of this thesis

The work is broken up into 7 Chapters. This chapter, 1, introduces the topic of steering position control for autonomous driving. The role of the EPS and the state of the art for steering system development in the context of autonomous driving were also presented.

Chapter 2 analyses the EPS system using an array of experiments to determine important characteristic which effect the behaviour of the system. The approach is firstly qualitative then quantitative as the model development is undertaken. The model parameters are thereafter generated using measurement data. Of particular focus is the modelling of friction. In this regards, a number of friction models are investigated on both the loaded and unloaded steering gear.

Chapter 3 uses linear modelling theory to develop controller synthesis models. Thereafter, a model reduction study is conducted and the chosen model is analysed in terms of controllability and observability. This chapter lays out the important characteristics in selecting a suitable model for controller synthesis.

Chapter 4 begins with the development of the control requirements and explains the problem of steering wheel oscillation. Both classical and state space control