

Design and Simulation of Steer by Wire for Light Electric Vehicle



Dawit Zewude Mitiku

A Thesis Submitted to

The Department of Mechanical Engineering

School of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfillment of the Requirement for Master of Science in
Automotive Engineering

Office of Graduate Studies

Adama Science and Technology University

November, 2022

Adama, Ethiopia

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Advisor: Dr. Alemayehu Wakjira

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DECLARATION

I hereby declare that this Master Thesis entitled “Design and Simulation of Steer by Wire for Light Electric Vehicle” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Name of the student

Signature

Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “Design and Simulation of Steer by Wire for Light Electric Vehicle” prepared under my guidance by Dawit Zewude Mitiku submitted in partial fulfillment of the requirements for Master of Science in automotive engineering. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Major advisor

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APPROVAL PAGE

I, the advisor of the thesis entitled “Design and Simulation of Steer by Wire for Light Electric Vehicle” and developed by Dawit Zewude Mitiku, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Dawit Zewude have read and evaluated the thesis entitled “Design and Simulation of Steer by Wire for Light Electric Vehicle” and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfilment of the requirement of Master of Science in Automotive Engineering.

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ACRONYMS

ACO	Anti Colony optimization
AFS	Active front steering
ANFIS	Adaptive Neuro-Fuzzy Inference System
ASM	Adaptive Sliding Mode
BBW	Brake by Wire
BFO	Bacteria Foraging Optimization
BLDC motor	Brushless DC motor
CAN	Controller Area Network
DC	Direct Current
DABW	Dual Redundancy Steer by Wire system
ECU	Electronic Control Unit
EHPS	Electro-hydraulic power-assisted steering
EPS	Electric power assisted steering
ESC	Electronic Stability Control
FLC	Fuzzy Logic Controller
FOA	Fruit Fly Optimization Algorithm

FOPID	Fractional Order controller
GWO	Grey Wolf Optimization
GA	Genetic Algorithm
HPAS	Hydraulic power-assisted system
IAE	Integral Absolute Error
ISE	Integral Square Error
ITAE	Integral Time Absolute Error
LQR	Linear Quadratic Regulator
MPC	Model Predictive Control
PID	Proportional Integral Derivative
PSCU	Power Steering Control Unit
PSO	Particle Swarm Optimization
SBW	Steer by wire
SMPC	Sliding Mode Predictive Tracking Control
TBW	Throttle by Wire

LIST OF SYMBOLS

B_{m1}	Steering motor damping
B_{sc}	Steering column damping
$F(fr,r)$	Rack frictional force
h	Ground clearance
H	Total height of the vehicle
I_{a1}	Current of steering motor
I_{a2}	Current of front motor
J_{m1}	Motor moment of inertia
J_{sw}	Steering Lumped inertia
K_{b1}	Steering motor emf
K_{s1}	Lumped torque stiffness (SM)
K_{sm}	Steering motor torque constant
l	Length of the vehicle
L	Wheel base
$L1$	Motor electrical inductance (SM)
m	Gross vehicle weight
$R1$	Motor electrical resistance (SM)

T_a	Self-aligning torque
T_{m1}	Torque of steering motor
T_{dr}	Torque of driver
T_{frc}	Torque of friction
$T(fr.kp)$	King pin torque friction
T_{m2}	Torque of front motor
V	Speed of vehicle
V_{s1}	Voltage source
V_{s2}	Front motor voltage
w	Wheel Track (width)
yr	Rack displacement
θ_{m1}	Angular displacement of steering motor
θ_{m2}	Angular displacement of front motor
θ_{sw}	Steering angle
δ_f	Front tire angle

ABSTRACT

The evolution of the vehicle steering system began with pure mechanical generation and progressed via hydraulic power-assisted steering (HPS), electro-hydraulic power-assisted steering (EHPS), electric power-assisted steering (EPS), and Steer-by-Wire (SBW) systems. In SBW the conventional steering system's hand-wheel link with the front wheels is eliminated, and instead, two electric motors are used to drive the front wheels and supply power to the vehicle driver for steering feel. In this thesis, the mathematical modelling of SBW systems is first explored, and two PID controllers designed to control the steering wheel angle and front wheel angle. The designed controller for SBW systems provides a comparative analysis of different optimization algorithms used to control tire angle and reveal the effect of system performance with disturbance and without disturbance at different driver torque input and steering angle. The simulation results show that the proposed vehicle steer by wire (VSBW) optimized by GWO algorithm produces 0.6032% overshoot and 0.1105s settling time which is lower than GA-PID and Auto-PID controller. That means its speed of response increased, stable and reduced energy consumption to reach its desired tire angle positions. The GA and Matlab auto tuner have 2.1263% and 7.5229% overshoot, 0.2293s and 0.1983 settling time, respectively. This shows that the PID controller designed using GWO can effectively and efficiently control the operation of steering angle motor and tire angle while ensuring the comfort of driver and ensuring a smooth driving system. Finally, the simulation result reveals that GWO-PID controller strategy has smooth operation by reducing the vibration that occurs by the overshoot.

Keywords: – Genetic algorithm, Grey wolf optimization, MATLAB/Simulink, PID controller and SBW.

CHAPTER ONE

INTRODUCTION

1.1 Background

The evolution of the vehicle steering system began with pure mechanical generation and progressed via hydraulic power-assisted steering (HPS), electro-hydraulic power-assisted steering (EHPS), electric power-assisted steering (EPS), and SBW systems (Mortazavizadeh et al., 2020a).

Electric power steering is a steering system which eliminates the need for a hydraulic power steering pump, hoses, hydraulic fluid, drive belt and pulley on the engine, therefore the total system is lighter than a comparable hydraulic system through the use of compact system units. Furthermore, because EPS is an on-demand system that only runs when the steering wheel is rotated, the fuel efficiency of vehicles equipped with it is up to 3% greater than vehicles equipped with an equivalent-output hydraulic system (Rezaei & Sadjadian, 2011).

In conventional vehicles, the steering hand wheel is connected to the road wheels through a link that can be mechanical, hydraulic or a combination of both. The design of a Steer-by-Wire (SBW) system eliminates such a link. The steering command is transmitted by a communication network and is powered by an electric drive coupled to the steering rack or by a pair of electric drives each of them directly coupled to a road wheel. A small-power electric drive is also mounted on the hand wheel to provide the driver with a feeling of the steering effort.

Drive-by-wire is one of the most precise and currently used technology in the automobiles field. It ensure to develop the way cars are being driven today with whole new experience for the driver. It also has new features, which were once only dreamt of. It is nothing but combination of mechanical and electronics engineering sides which gives a totally different product. This technology may be new to the automobile field but it has been practically in use for last few decades in aerospace industry where fly-by-wire technology used in most of the new planes, which is similar to, drive-by-wire (Arango et al., 2020).

This thesis mainly concerned about locally assembled HYUNDAI electric light vehicle; its spare parts are imported from South Korea and assembled in Addis Ababa. Nowadays the electric

vehicle is a widely used car around the world because of this Athlete Haile G/Sillasse owner of Marathon Motors started assembling this car in 2020 in Addis Ababa. Also many different electric cars are imported from many countries according to customer request. The purpose of this study is to design and simulate a steer by wire; with this design is expected to reduction of driver's effort with accurate steering system.

The motivation for introducing steer-by-wire systems can be attributed to three aspects:

- **Functionality**

Although today's electromechanical steering systems enable features such as speed-dependent power assistance for vehicle stabilization and lane-keeping assistance for vehicle guidance, the mechanical part of the system limits the functionality when torque is transferred between the steering wheel and the steering system. As a result, the steer by wire compensates for the change in steering torque caused by the active front steering driver's needs. (Eckstein et al., 2014).

- **Vehicle architecture, including benefits in production and costs,**

The steering system's mechanical integration has a significant impact on the vehicle package. Because the ergonomically required location and angle of the steering wheel mainly changes with the varied postures of the driver, the geometry of a traditional steering system limits the vehicle variants that can be derived on a modular basis. Implementing steer-by-wire results in a more robust steering system and engine compartment, as well as a wider range of vehicle types on a single technical platform.

- **Human factors**

In aviation industry the pilot's ability to control the aircraft without considerable auxiliary forces and flight control systems rapidly deteriorated as aircraft size and performance increased. As a result of the advent of fly-by-wire, which uses small joysticks instead of massive column sticks, the entire pilot compartment arrangement has changed. Furthermore, by incorporating by-wire controls in a road vehicle, the driver compartment layout can be considerably improved in terms of human factors, design, active safety, and passive safety (Eckstein, L, n.d.), 2001.

1.2 Statement of the Problem

Today's technology development in automotive industry reached autonomous and electric vehicles are available on the roads. In Ethiopia the government supports electric vehicles for transportation and customer also interested on this vehicles because of safety, comfort and great performance. To decrease the number of second hand vehicles on a road recently the government increased a second hand vehicles importing tariff because of emission and low performance which mainly causes accident. Initially these used vehicles are right hand wheel drive but when they come to our country with a little modification they changed to left wheel drive so at high speed on the highway road they are making many accidents because of steering system problem many damages are happening in our country.

Several researchers studied the modeling and control of steer by wire system with traditional tuning PID parameters like Ziegler Nicholas method (Zaidi et al., 2017) and standard approach (Fahami et al., 2012). Only few researcher focus on PID controller tuning algorithm with particle swarm optimization (PSO) and others optimization algorithm in this algorithms when the driver turns the steering wheel they get slower output response when compared with steer by wire of tuned by grey wolf algorithm (GWO) as shown in simulation results with disturbance and without disturbance. An improved grey wolf optimizer used in to reduce tiresome effort required to tune the PID parameters and inaccurate system behavior.

To address this problem, the SBW technology is modeled and controlled by PID controller with different tuning algorithm; modelling and simulation of SBW is carried out in this study, to get highly efficient steering response or fast vehicle steering response capability.

1.3 Objectives of the Study

1.3.1 General Objective

The general objective of this thesis is to design and simulate steer by wire for light electric vehicle specifically for HYUNDAI car.

1.3.2 Specific objective

The specific objectives of this research thesis work are:

- ✓ To perform the simulation of a Steer by Wire based on a mathematical model.

- ✓ To design a PID controller for a Steer by Wire light electric vehicle.
- ✓ To tune controller (PID) parameters using Grey wolf, Genetic algorithm and MATLAB auto tuner optimization algorithms.
- ✓ To evaluate the performance of the developed steer by wire in MATLAB/Simulink using a standard approach.

1.4 Significance and benefits of the Study

The significance of this thesis work are as follows:

1. Increased vehicle design freedom: as the electromechanical components occupy less place compared to the mechanical counterparts, and the control modules can be placed wherever the design permits.
2. Improved Safety: Systems such as electronic stability control (ESC), adaptive cruise control, and Lane Assist Systems can improve safety by allowing for computer-controlled intervention of vehicle controls.
3. Increased Driver Comfort: It is normal to use variable steering ratios to increase driver comfort by lowering the ratio in the parking lot and raising the ratio to normal when traveling on the highway.

1.4.1 Beneficiaries

- ✓ Automotive industries
- ✓ Society and
- ✓ Government

1.5 Scope of the study

The thesis focuses on the mathematical modelling and simulation design of steering wheel system, front wheel system and steering feel. Simulation of overall SBW system control technique is using MATLAB/Simulink for electric vehicle application are implemented. The performance of SBW with different tuning algorithms are developed and discussed. Finally, to show SBW left and right turn; its simulation is done on Proteus software.

1.6 Limitations of the Thesis

The thesis is limited to the simulation of the system using MATLAB/Simulink and demonstration model by showing how the different components of the system interact with each other. This is because the implementation of a real system is difficult to procure the components. Along with it, it takes the additional time and cost incurred in making the actual prototype implementation.

1.8 Thesis Organization

This thesis is organized into five chapters.

Chapter 1: - Introduction: This includes the background of the study, statement of the problems, objectives, significance, scope and limitations of the research.

Chapter 2:- Literature review: This chapter includes a literature review on design and simulation of steer by wire and related work.

Chapter 3:- Materials and Methods: Describes the materials and methods followed in this thesis, materials used for a model and the mathematical model of the steer by wire and steering feel generation. This chapter also presents the control design (PID) and optimization algorithms (GWO and GA).

Chapter 4:- Results and discussions: This chapter describes results of different simulations resents the proposed results and discussions

Chapter 5: - Conclusions and recommendation: This chapter concludes the findings of the work conducted and recommendation for future research in the form of summary

CHAPTER TWO

LITERATURE REVIEW

2.1 Steering system

The steering system of ground vehicles is generally classified into **(i)** Mechanical steering systems **(ii)** Hydraulic- and Electro-hydraulic-power-assisted steering (HPAS and EHPAS) systems (Ammon et al., 2006) and **(iii)** Electric-power assisted steering (EPAS) systems.

The intermediate mechanical link used to connect the hand-wheel to the steered front wheels through the rack and pinion gearbox is still kept on the hand wheel side, which is obviously the common point of these three assisted steering methods. Unfortunately, using a mechanical shaft with a set gear ratio makes it difficult to help the driver in adjusting the steering command in response to various driving situations and environments, as well as the vehicle's state. In addition, in the event of an accident, the steering shaft could be a harmful component for drivers.

A vehicle steering system is a set of devices utilized to change or maintain the direction of a vehicle during running or reversing. The function of vehicle steering systems is to control the running direction of vehicles according to drivers' command. The steering performance of a steering system is very significant for a vehicle's maneuverability and safety. Thus, the development of vehicle steering system has attracted a great deal of attention from the industry and academia about automobile manufacturing.

To address the issues, by-wire technology, which has already been fully implemented in modern aircraft's fly-by-wire flight control systems, is being introduced to replace mechanical or hydraulic systems with electronic systems. Automakers have also used by-wire technology for throttle and brakes in production vehicles, such as Throttle by Wire (TBW) and Brake by Wire (BBW) systems, with the benefits of decreased power usage and improved vehicle control. The next critical goal is to incorporate the new technology into the next generation of steering systems, known as SBW systems (H. Wang, 2013).

As discussed in Chapter 1, SBW systems have several potential advantages over conventional steering systems, including improved overall steering performance and vehicle stability control,

lower automotive power consumption, and increased safety and comfort for drivers and passengers during normal driving and emergencies.

2.1.1 Conventional mechanical steering system

In conventional mechanical steering system, the column shafts are directly connected to rack pinion gear and tire system, existing conventional steering system use hydraulic power steering (HPS) or Electric power steering (EPS) to assist the driver (Fahami et al., 2012). The conventional steering system that can be modelled as a multi-mass system is composed of several basic components as shown in Fig. 2.1 the hand-wheel, the steering column, the mechanical shaft, the steering rack, the pinion, the tie rods connecting the steering rack to the steered wheels, the steering arms, and the two steered wheels (H. Wang et al., 2014a).

(Wu & Li, 2020) studied the problems of large free travel, heavy steering and slow response of the existing mechanical steering system of electric tractor, a steer-by-wire system directly driven by linear actuator. They theoretically examined the steer-by-wire steering process and used MATLAB/Simulink to simulate the model. The steering system's reaction and step response were modelled and evaluated. They performed with in steering test and a road-drive test on the modified prototype to evaluate the steering performance of the steer-by-wire system in an electric tractor.

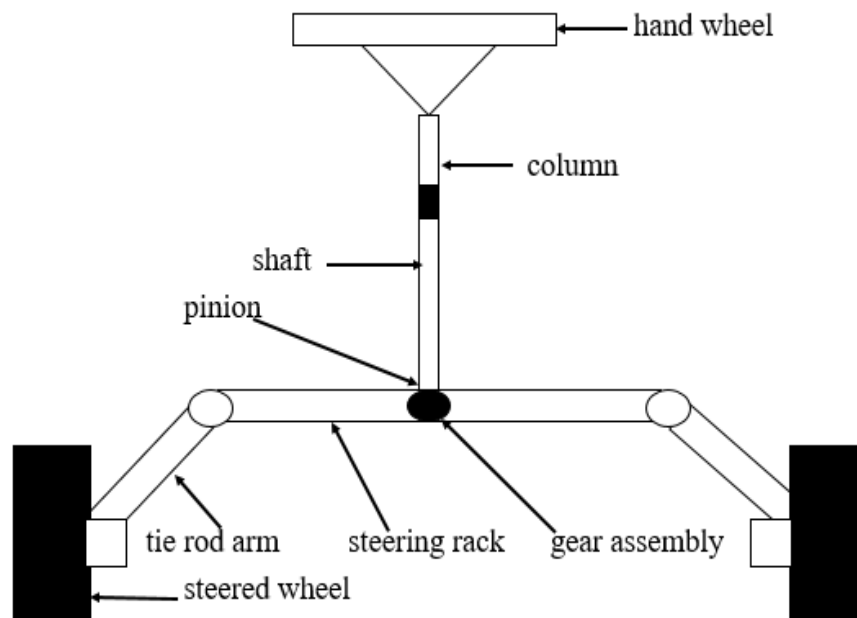


Figure 2.1: Conventional steering system (H. Wang et al., 2014a).

Their findings reveal that the designed steer-by-wire system can satisfy the requirements of low-speed electric tractor driving, with quick response, steady steering, and good overall tracking performance.

2.2 Power Assisted Steering Systems

2.2.1 Hydraulic-power-assisted steering system

The invention of HPS system is recognized as a great improvement introduced in 1951 by Chrysler Imperial (Eckstein et al., 2014). It needs less driver's effort and achieves faster response supported with more stability and safety compared to its predecessor. The hydraulic oil helps in less vibration appeared on steering hand-wheel (HW). The HPS system was later upgraded to the EHPS system due to the high expenses of its design, assembly, and maintenance.

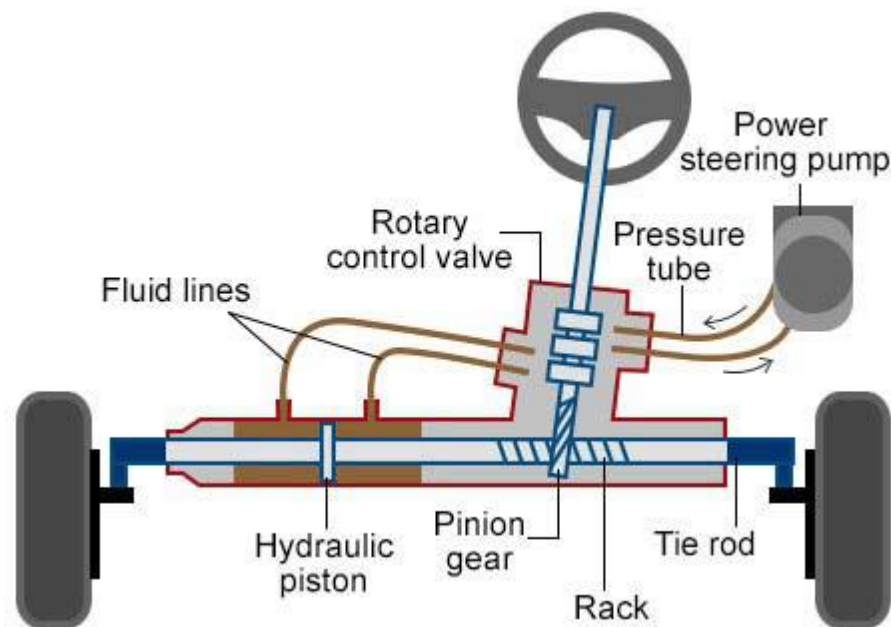


Figure 2.2: Structure of a hydraulic-power-assisted steering system (Z Sun, 2017)

(Mohamed & Albatlan, 2014) proposed SBW with integrated hydraulic power steering (HPS) in commercial vehicle. Their mathematical model was used to evaluate the performance of the SBW system using Matlab/Simulink software, a PID controller, and Linear Quadratic Regulator (LQR) optimization techniques to arrive at an optimal controller for the SBW to monitor the system's dynamic behavior and stability characteristics. This SBW system consists of a microprocessor and

interface circuits for active DC motor control. Practical test steering response is influenced by variables such as front axle weight, dampening, and changing friction conditions. SBW's experimental results show that it is possible to attain great performance and robustness.

2.2.2 Electric-power-assisted steering system

EPS system is a combination and interactive systems of electric and mechanical, it is also a vehicle control subsystem, in order of the EPS system to ensure accurate vehicle steering control and maneuverability, at first, there must be a reliable model to fully examine the intrinsic properties of subsystems. Second, vehicle handling dynamics and electric power steering system dynamics must be considered to analyze the effect of the subsystem parameters on the steering performance.

The basic structure of an electric-power-assisted steering system is shown in Figure 2.3. In an electric-power-assisted steering system, sensors are utilized to detect the position and torque of the steering column, and an electric motor usually connected to the steering gear or steering column is utilized to generate assisting torque to assist the driver of a vehicle (Marouf et al., 2012).

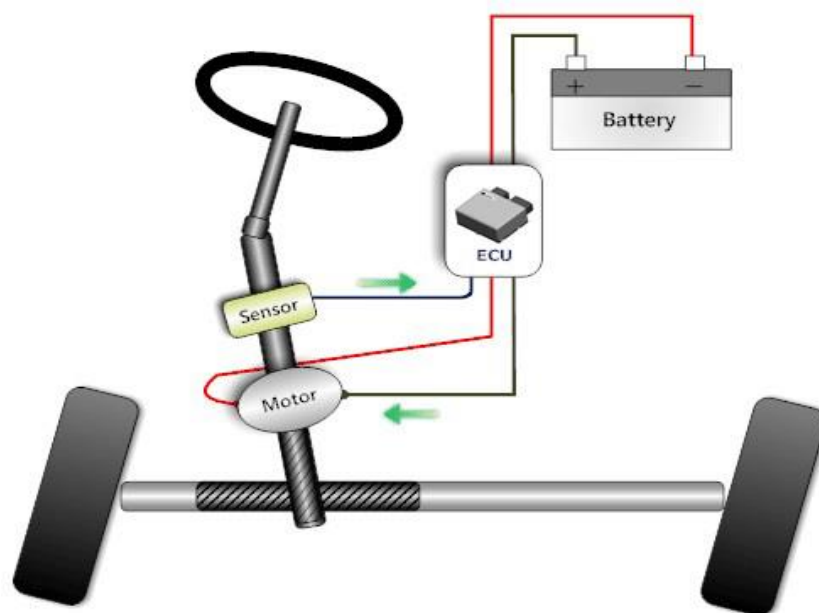


Figure 2.3: Structure of an electric-power-assisted steering system (Z Sun, 2017)

The advantage of EPS compared to HPS is the system comparatively new technology with less complicated build mechanism, taking less space and more durable (Mortazavizadeh et al., 2020b). After analyzing the dynamics of the EPS system, a model of the EPS system is created, and the characteristics of the EPS system are merged to create a PID controller with emendation function in series. This control approach with the mathematics, according to the test results, has had a positive effect in lightening the handle force and heightening the return back to the middle position (Huijun & Youde, 2012). The objectives of the EPAS control system are to ensure appropriate assisted torque, system stability, vibration attenuations, improved hand-wheel return ability and freely controlled performance.

2.3 Steer-by-Wire system

By-wire steering technologies started with fly-by-wire system used in Concord civilian aircraft in 1970s (Huang et al., 2017) where, mechanical link was replaced with steer by-wire electrical connection. Subsequently similar systems using this concept such as brake-by-wire, throttle-by-wire, shift-by-wire (also known as gear-by-wire) and steer-by-wire have been introduced for automobile application. SBW (steer-by-wire) is the most major X-by-Wire Technology that will change the automotive industry. As shown in Figure 2.4, an SBW system consists of electronic control units, steering assist motors, and sensors that might potentially replace mechanical steering column linkages in a vehicle (Huang, Naghdy, Du, et al., 2019).

In steer-by-wire system, there is no mechanical coupling between the steering wheel and front wheel system. Even though the mechanical coupling between the steering wheel and the front wheel system are eliminated, a steer by wire system expected not only implement same function as conventional mechanical coupling steering system, but it expected to provide advanced steering function (Fahami et al., 2012).

(Mi et al., 2021) studied how to solve the most critical problem of SBW in its practical application. A dual-redundancy steer-by-wire system (DSBW) is used to solve the safety reliability problem of SBW by applying the redundancy theory, which states that no system failure occurs when any single random electrical fault occurs, indicating that DSBW is a system-level dual redundancy system rather than a system with local redundancy. Finally, a DSBW prototype is built to

demonstrate its high level of safety reliability. Fault injection trials of the system are carried out, in which DSBW operates normally in the presence of a single electrical failure.



Figure 2.4: Structure of a steer-by-wire system (Y. Han et al., 2014).

(Y. Han et al., 2014) investigated an experiment and simulation on Steer-by-wire system can improve the performance of vehicle handling stability. By removing the mechanical links between the front wheels and the steering wheel, a key force feedback mechanism for steer-by-wire systems can be achieved. They proposed a method for designing torque ratio based on the steering wheel torque characteristic for steer-by-wire system in light of the characteristic of variable torque transmission ratio for steer-by-wire system, and the results show that the design goal was met and the steering wheel torque characteristic obtained is very similar to that of the reference car.

(Marumo & Nagai, 2007) carried out research successfully a steering control method to improve motorcycle handling and stability. Steer-by-wire (SBW) technology is applied to the motorcycle's steering system to eliminate typical vehicle maneuvering challenges. The actual rolling angle of

the SBW motorcycle is regulated by computer simulation using a simplified motorcycle model to follow the desired rolling angle specified by the user.

Active Front Steering systems are known for improving handling by adjusting the steering ratio based on vehicle speed and steering-wheel angle. A new overall idea is proposed that includes lateral and longitudinal acceleration, as well as steering rate, all of which are available signals in a production vehicle (Sterthoff et al., 2021). The four-wheel steer-by-wire vehicle (FSV), which combines the steer-by-wire (SBW) and four-wheel steering (4WS) systems, can improve vehicle safety and efficiency while also increasing steering flexibility (Zhao et al., 2018).

(Fahami et al., 2012) proposed the control strategy for the wheel synchronization and the variable steering ratio. The steering wheel and front wheel models were developed using mathematical modeling. The PID controller is used to command the steering wheel and front wheel system, and it introduces a new feedforward variable steering ratio based on the under propensity equation approach. To analyze the system performance, a simulation was created and compared.

Thus, a fault-tolerant control system is critical in SBW vehicles. This requires quick fault detection and identification algorithms, and the ability to maintain overall system stability and acceptable performance in the case of component failure. Tolerance to actuator faults is a key issue in SBW systems as the wheel fails to provide the expected torque when the actuator fails, undermining the vehicle motion control and resulting in an unsatisfactory performance or even instability (Huang, Naghdy, Du, et al., 2019).

2.4 Control Strategy

2.4.1 PID Controller with different Tuning Algorithms

Optimization of PID parameter using Imperialist Competitive Algorithm (ICA) to control lateral and yaw motion that applied to the simulation of vehicle models. The proposed optimization then compared with standard PID controller. The main advantage of proposed optimization is faster and more accurate compared with standard PID controller. And then the error of the controller is reduced too. The results obtained are of vehicle motion can be maintained in accordance with the desired trajectory with smaller error and was able to achieve higher speeds than with the control system using optimized without parameters (Ali et al., 2015).

(Suman & Giri, 2016) studied a speed Controller of a DC motor by decision of a PID parameters using Genetic Algorithm (GAs), the DC motor is widely used as a part of various applications, for example, steel plants, electric trains, cranes and significantly more. Their goal was to design PID parameter optimization algorithms. They have sketched out a freely energized DC motor using MATLAB, whose speed can be studied using the Proportional, Integral, Derivative (KP, KI, KD) expansion of the PID controller. The Genetic Algorithm (GA) was developed to optimize PID controller parameters for DC speed control and to rundown its benefits over traditional tuning strategies. The results obtained by GA figuring were distinguished from those obtained through a conventional technique. It was discovered that optimization methods outperform traditional PID controller pattern tuning practices.

To optimize PID controller parameters, a novel tuning method based on the Fruit Fly Optimization Algorithm (FOA) is developed (J. Han et al., 2012). The position of each fruit fly illustrates a possible PID parameter solution. The evolution of each iterative swarm is addressed as the fruit fly swarm flies towards one destination. The tuning results - the best PID controller parameters - can be acquired after hundreds of iterations. The proposed method has several advantages, including ease of implementation, a stable convergence characteristic, a vast searching range, ease of converting such an idea into program code, and ease of comprehension. The FOA Based Optimized PID (FOA - PID) controller is capable of giving satisfactory closed-loop performance, according to simulation results.

(Chao & Weixing, 2006) based on the conception of evolution, the Particle Swarm Optimization (PSO) algorithm and Genetic Algorithm (GA) they applied to parameters optimization of PID controller. Simulations are carried out in the typical industrial models. When comparing the performance of PSO with GA, it is shown that PSO exceeds GA, and that PSO is a better strategy for optimizing PID controller parameters.

(Das et al., 2016) developed a bio-inspired meta-heuristic soft computing strategy for improving the performance of a PID controller for DC motor speed control. An evolutionary method based on Grey Wolf Optimizer is utilized to optimize a PID controller for an implemented second order DC motor system. In MATLAB/Simulink environment, the best set of PID parameters thus obtained from the optimization are used with a step input to the DC motor to get the transient response specifications such as rise time, settling time, maximum over shoot and steady state error.

These results are then compared with results from other conventional techniques and soft computing methods to look for the most efficient method to get best transient response in a DC Motor.

(Raja et al., 2017) designed the controller for balancing a bicycle. As bicycle is highly nonlinear system it is very much difficult to design the controller. The Proportional Integral Derivative (PID) controller based on intelligent controllers like Bacterial Foraging Optimization (BFO), Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) are designed and comparison is made between them to find which will give the better result for the bicycle. A nova test is taken to compare the error values and it is found that ACO based PID gives better result.

To regulate the angular position of the rotary actuator, which controls the moveable surface of space vehicles, a proportional integral derivative (PID) controller was constructed and linked to an electro-hydraulic servo actuator system (EHSAS). The genetic algorithm is used to optimize the PID gain settings (GA). The controller is tested using the SIMULINK program on a novel state-space model of servo-valves connected to a physical rotary actuator. Experiments are used to test the controller and the state-space model (Elbayomy et al., 2008). In comparison to the traditional PID controller and the compensator controller, simulation and experimental data show that the PID controller adaptive by GA is more effective at controlling the angular position of the rotary actuator.

(Soon et al., 2017) dealt with an evaluation on the designed controller named as sliding mode control (SMC) which sliding surface of the controller has been integrated with proportional-integral-derivative (PID) controller. The control scheme is established from the derived dynamic equation which stability is proven through Lyapunov theorem. In order to evaluate the performance of the developed PID sliding surface, the controller parameter is first produced using the Ziegler-Nichols (ZN) tuning method, which is then compared to the particle swarm optimization (PSO) computational tuning approach. The PSO tuning algorithm outperforms the usual ZN tuning approach in terms of trajectory tracking on the electro-hydraulic actuator (EHA) system, according to simulation data.

FOPID

(Cao et al., 2005) presented the intelligent optimization method for designing Fractional Order controller (FOPID) based on genetic algorithms. Because of the arbitrary order of fractional calculus, it can give a novel and effective performance enhancement for FOPID. The parameters of FOPID controllers are proportional constant, integral constant, derivative constant, derivative order, and integral order, with a more complicated design than a traditional integer order PID controller. The numerical simulation of FOPID controllers uses the Tustin operator and continuous fraction expansion. The optimal design process based on evolutionary algorithms is examined in depth, with the optimization performance target being a combination of ITAE and control input. The proposed strategy is highly effective, according to simulation results.

2.5 FLC, LQR and Steering Feel

The simulation model is performed in Simulink for various vehicle speed inputs and steering wheel angle step inputs, and yaw rate response characteristics are obtained, so the steering system control requirements are proposed, and a fuzzy logic control system is established. This control approach can help increase the vehicle's stability and responsiveness. Simulations are used to generate a set of transmission ratio curves that demonstrate the correctness of the suggested fuzzy logic control method (Geng et al., 2011).

(Li et al., 2021) applied a high-order control to a dynamical system with uncertainty. There are two characteristics. The first is a fuzzy description of the uncertain part, which is time-varying but bounded. The uncertainty is specifically contained within a fuzzy set, and the bound is considered a fuzzy number. With a deterministic controller based on the Lyapunov theory, the systems are uniformly bounded and uniformly eventually bounded. We use non-cooperative game theory to optimize the parameters by establishing a Nash game, which results in greater system performance and lower control input. For the uncertainty associated with fuzzy numbers, the D-operation is then proposed. Finally, we verify the steering-by-wire system by doing numerical simulations.

(Faieghi & Azimi, 2010) developed an intelligent agent based on Adaptive Neuro-Fuzzy Inference System (ANFIS) to perform a Non-linear Auto-Regressive Moving Average with eXogenous input (NARMAX) system identification of BLDC motor. At first they used exhaustive search technique to select the ANFIS inputs, and then by using Fuzzy C-Means (FCM) algorithm, an

ANFIS has been performed to approximate the motor characteristics. In the second part, an optimized Proportional-Integral-Derivative (PID) controller has been developed. Particle Swarm Optimization (PSO) has been used as an optimization algorithm to tune the parameters of the controller. All steps simulated by MATLAB resulted in notable performance.

The gain scheduling with a linear quadratic regulator controller is used to control the feedback torque and to vary a steering feel gain. A real-time hardware in the loop (HIL) methodology is built utilizing the Matlab XPC target toolbox to investigate the effectiveness of the suggested algorithm. The results show that the suggested algorithm can create feedback torque in the same way that an EPS steering system can. In addition, the compensatory torque can increase steering sensation and system stability (Muhammad et al., 2015).

(Baviskar et al., 2009) integrated a steer-by-wire system technology into ground transportation vehicles, allowing the human-machine haptic interface to be customized to meet the driver's chosen level of road "feel." The capacity to fine-tune the dynamic behavior of the steering system has the potential to improve the driver's overall performance and vehicle safety. The directional control steering assembly is designed to follow the operator's requested maneuvers at the driver interface, and a nonlinear tracking controller is used to ensure this. In addition, the driver receives customizable force feedback proportionate to the reaction forces at the tire-road interface from the controller. Two control strategies are presented to ensure that the corresponding tracking errors are pushed to zero asymptotically. The first adjusts for parametric uncertainty, while the second, by employing observers, eliminates the requirement for torque measurements. To demonstrate the controller's performance in various driving circumstances, numerical and experimental data are presented.

2.6 MPC and SMPC

(Bernardini et al., 2009) presented a hybrid Model Predictive Regulation (MPC) architecture for coordinated control of AFS and ESC. The vehicle dynamics are stated as a linear hybrid dynamical system by expressing the vehicle dynamics with regard to the front and rear tire slip angles and approximating the tire-force characteristics with piecewise affine functions. This model is used to design a hybrid model predictive controller. The proposed model formulation allows one to visually analyze the stability region of the closed loop system and to assess the stabilizing

capability of the hybrid MPC controller. Simulations of the controller in closed-loop with an accurate nonlinear model are presented.

(Huang, Naghdy, & Du, 2019) they presented a sliding mode predictive tracking control (SMPC) technique for an SBW system with uncertain dynamics to improve the robustness of model predictive control (MPC) in the presence of modeling uncertainties and disturbances in the steering control processes. For the steering angle tracking challenge, modeling and experimental findings show that the proposed SMPC tracking controller outperforms both SMC and MPC techniques.

(Huang et al., 2018) based on a delta operator method, they offer a new fault estimation and fault-tolerant model predictive control (MPC) scheme for an SBW system. To estimate the defect in the SBW systems, a fault detection observer based on linear matrix inequalities is built using delta operator systems. In the event of an actuator failure, an active fault-tolerant MPC based on a delta operator is designed to compensate for the influence of the actuator failures and offer vehicle road wheel steering operations without compromising tracking performance. The proposed scheme's effectiveness is demonstrated by the approach's validation using computer simulation.

2.7 Research Gap

The main contribution of this thesis is the design of a PID controller for successful tire angle direction control. The PID parameters are tuned using GWO, GA and MATLAB/Simulink auto tuner. Most of researchers designed PID controller with traditional tuning algorithms like Ziegler Nicholas method. Some researchers use PSO, ACO, BFO and other optimization algorithms to increase the efficiency of SBW. They did not consider the effect on steering efficiency and performance by using GWO algorithm and steering feel. The PID tuned using GWO algorithm has never been applied to light electric vehicle before and the main advantage of proposed optimization is faster and more accurate response when compared with standard PID controller and GA tuned PID controller, then the error of the controller is reduced too.

CHAPTER 3

MATERIALS AND METHODOLOGIES

3.1 Materials

In this research work, software such as MATLAB/R2021a, Proteus.Pro.8.13.SP0.31525, and Math Type 7.0 equation is used. MATLAB is the computing software that consists of technical toolboxes and Simulink; Proteus.Pro.8.13.SP0.31525 is used to simulate, design and drawing of electrical circuits. Microsoft office is used for writing the thesis documentation of the thesis. Math Type 7.0 is used for writing mathematical formulas and equations in Microsoft offices word 2016 and Power Point presentation tools.

3.2 Input Devices for Steer-by-Wire Systems

In a SBW system, when the driver applies torque to the steering wheel it is registered by the car as a control signal and an output is sent to the steering rack actuator. In some scenarios, a mathematical model of the vehicle can be used to calculate the corresponding torque that the driver should feel for the specific scenario, which is then generated by means of the haptic force feedback motor. The simpler approach is to use the actual forces acting on the steering wheels, which also feeds disturbances from the road to the driver.

SBW systems usually consist of the following components:

- I. Human Interface Device, traditionally a steering wheel.
- II. Sensors, for instance torque or angle.
- III. Haptic feedback actuator, usually a BLDC motor.
- IV. Steering rack actuator, usually the integrated power steering motor which translates rotational action to linear.

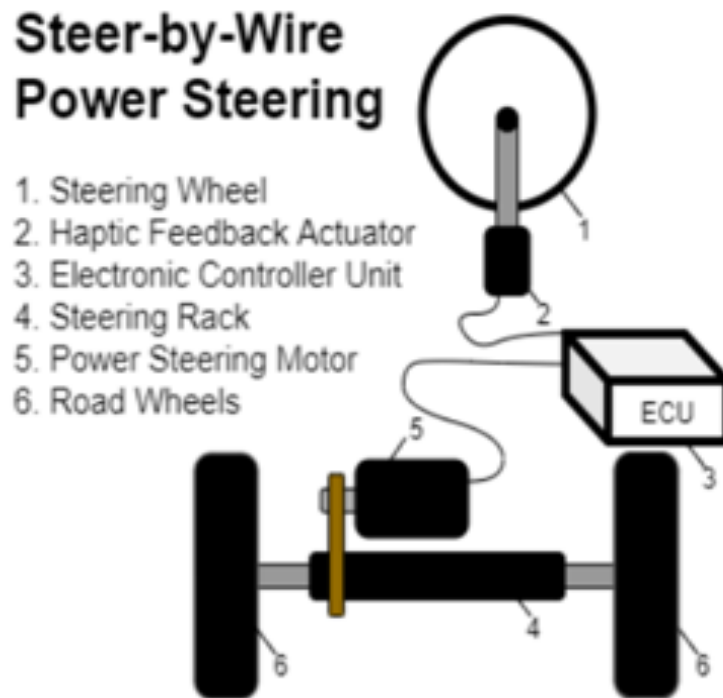


Figure 3.1: Components of SBW systems (Zhang, 2010).

With a full SBW system, the steering column is replaced by actuators and control systems to steer the car, a system overview is shown in Figure 3.1 with general components for both types of steering systems. Since steering is one of the most safety critical systems of a car, redundancy and fail-safe procedures needs to be implemented in other ways.

3.2.1 Electronic control unit (ECU)

With increased complexity regarding sensors and actuators in passenger cars, the ECU is a type of embedded system that controls one or more actuators to achieve a specific function. The control unit receives electrical input signals from all the relevant sensors and outputs electrical control signals to all the actuators used to perform the specific tasks.

The electronic control unit used in EPAS systems is called electric power steering control unit (PSCU). Driver steering input signals in terms of torque and speed of the steering wheel with absolute precision are sent to the PSCU, which calculates required steering assistance from the servo motor based on position, rotational speed and direction of the steering wheel. The control

unit also verifies sensor signals and can detect faulty components (“Automob. Electr. Electron. Syst.,” 2017).

Modern vehicles today typically contain more than 70 ECUs that controls different safety-critical systems. The most relevant bus standard used for communication between controller units, sensor and actuators for the project is called Controller Area Network (CAN) and will be described in the following section.

3.2.2 Controller area network (CAN)

The Controller Area Network (CAN) was developed in 1985 by Bosch as a method to have robust communication between the growing numbers of electronic subsystems in cars. The system is today fully adopted in the automotive and other electro-mechanical industries. It is used as a standard for transmitting data between different ECUs in modern vehicles and is since 1993 international standard, *ISO11898* (Zhang, 2010).

The structure of CAN messages includes several bits that are used for transmission of information and error checking. These are however not relevant for many users and the actual information that is sent and received in CAN messages consists of two main functional components, the identifier and the data. The identifier tells the protocol what the signal is, while the data contains the information of the signal.

The identifier is traditionally made from 11 bits, there are however newer expansions of the protocol that offers up to 29 bits (*William Bolton*, n.d.), 2003.

In order to obtain and send data to and from the steering device, CAN will have an integral role. The communication will be integrated with offline controllers deployed in HIL prototyping platforms, such as dSPACE Autobox or a Vector VN-modules (Christiansen et al., 2020).

All the systems mentioned above are for instance subject to ISO26262, a unified safety standard for vehicle electrical and electronic safety-related systems. The increasing complexity of vehicle electronic systems lead to the introduction of the risk-based safety standard intended for passenger cars with a focus on safety critical components during all phases of the product life cycle (Ji et al., 2013).

3.2.3 Force feedback in Steer-by-Wire systems

When the mechanical steering column is removed, new solutions for force feedback torque generation is required. The EPAS motor commonly used in steering gears is a brushless synchronous motor (BSM) which is also often used as force feedback motor in SBW applications. This thesis will investigate the possible benefits and implications of using a smaller DC motor.

The general principle of an electric motor is converting electrical energy to mechanical energy. Electric motors are categorized by type of supply current; alternating current (AC) or direct current (DC). The DC type motors are then typically divided into two groups based on the type of construction and commutation. The first is a brushed type, where the rotor has coil windings and the stator is either a permanent magnet or an electromagnet (*William Bolton*, n.d.), 2003.

3.2.4 Brushless DC motor

The trapezoidal back-emf synchronous motor which is called brushless DC (BLDC) motor is receiving wide attention for industrial applications because of its high torque density, high efficiency and small size. This kind of electrical motors is a typical example of highly coupled, nonlinear systems (Faieghi & Azimi, 2010). Brushless DC motors (BLDC), are DC motors that instead of using commutator brushes to reverse the electric polarity, uses electronically controlled energizing of the windings to generate torque. They have in recent years increased in popularity due to advances in commutator circuits.

This thesis will utilize BLDC motors as feedback due to overall good power to size ratio. The construction of the brushless type of DC motors is reversed compared to brushed types, the rotor is a permanent magnet and the stator has the coil windings.

This type of motors has three windings, with each winding being capable of reversing polarity, the motor goes through six different voltage phases in each revolution. Due to the energizing of the coils only depending on where in these six steps the motor is, the resolution of any sensor only has to be 6 pulses/rev to be able to control the commutation. This is why most BLDC motors comes with three internal hall-sensors used to control commutation. The Hall-sensors are capable of

detecting positive or negative magnetic fields and hence provide sufficient resolution (*William Bolton*, n.d.), 2003.

Four quadrant (4-Q) BLDC motor control

BLDC motor control is split into different quadrants dependent on direction of rotation and torque. The simplest controller acting in quadrant one and three can only apply torque in the same direction as rotation. Controllers also acting in quadrant two and four can provide torque in the opposite direction of rotation and are called 4-Q controllers. This means that the motor can act as a brake when the torque is applied in the opposite direction of the rotation. This is a requirement in force feedback implementations in order to supply the driver with feedback torque in the opposite direction of the steering input rotation (Christiansen et al., 2020).

3.2.5 Sensors

Sensors primarily used in SBW systems are torque and angle sensor which will be briefly explained in this section.

a. Angle sensor

Angular displacement can be measured by digital outputs from optical encoders which can be divided into two categories: incremental encoders and absolute encoders.

b. Incremental encoder

The encoder consists of a rotating disc with slots combined with a light source and sensor. When the disc rotates the light sensor outputs a pulse proportional to the rotated angle. Usually the disc consists of three tracks, two are the same spacing with a small offset in order to determine the direction of rotation. The resulting signal from this can be seen in Figure 3.2, where A and B are separate sensors that are offset. The final track only consists of one slot and is used to locate a type of home position.

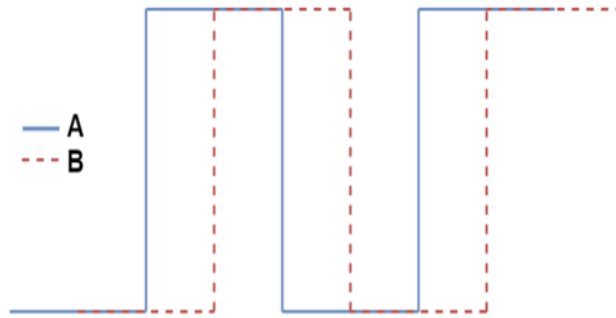


Figure 3.2: Typical encoder pulse train (*William Bolton, n.d., 2003*).

The Figure below shows the simulation, design and draw of electronic circuits SBW system in Proteus.

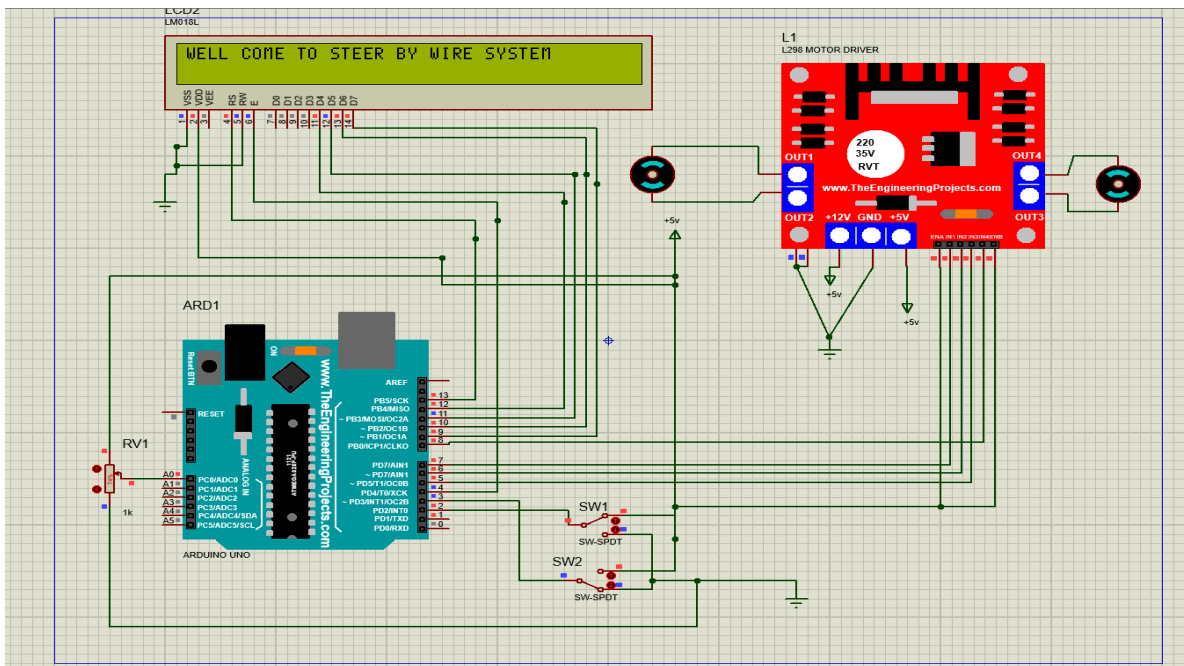


Figure 3.3a: Welcome to steer by wire system

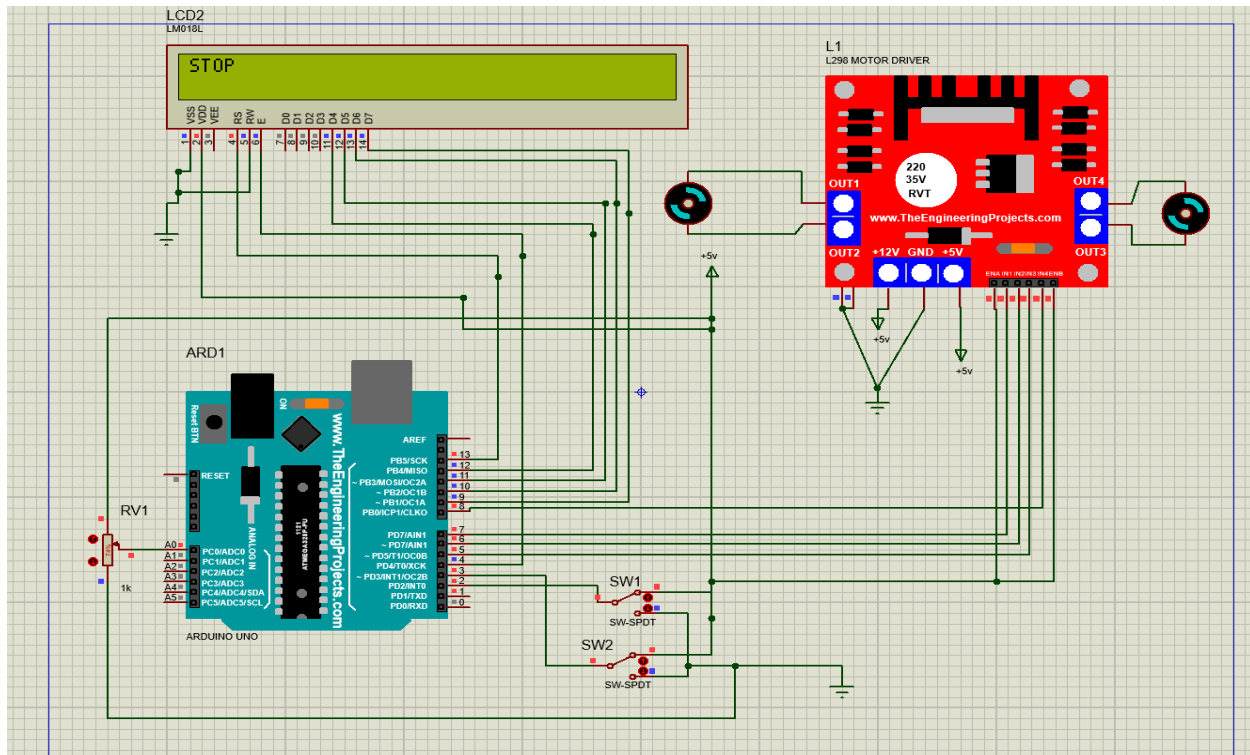


Fig. 3.3b: The initial condition at stop.

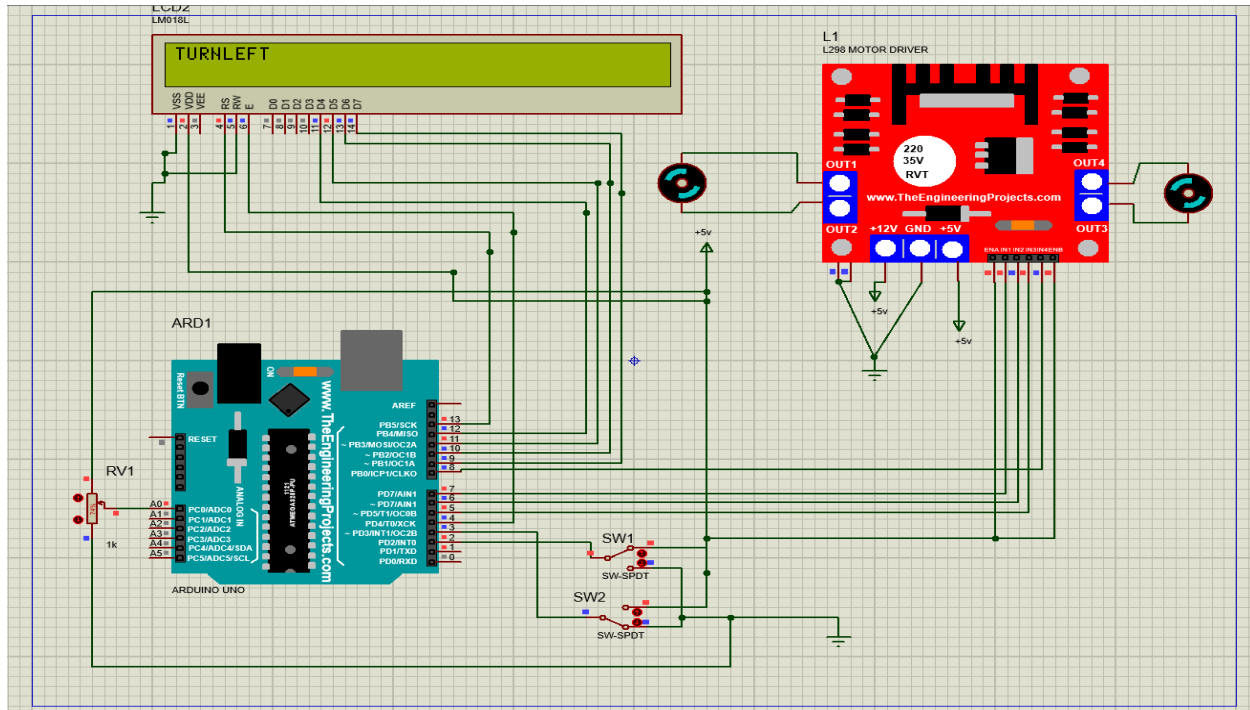


Fig. 3.3c: The steering wheel turn to the left.

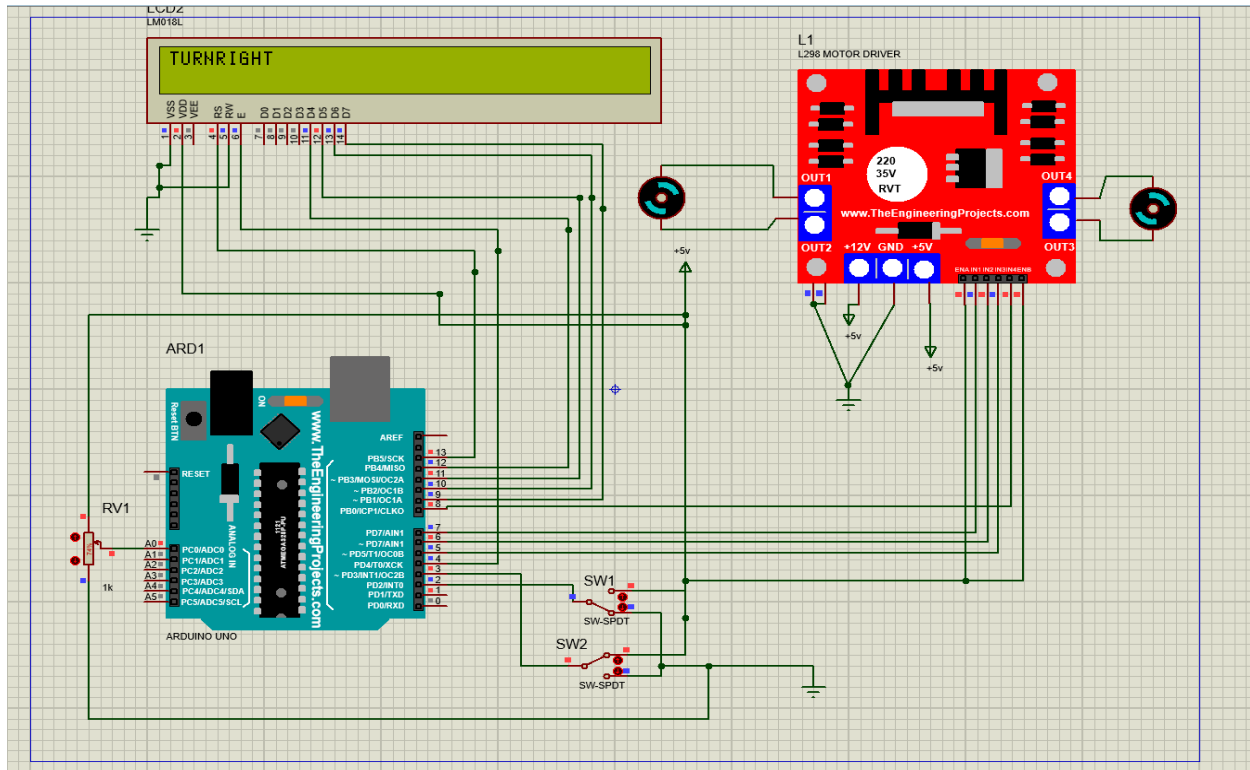


Fig. 3.3d: The steering wheel turn to the right.

c. Absolute encoder

The basic principle of the absolute encoder is an extension of the incremental where the tracks forms a specific binary number for each angular segment. The total number of bits in the binary number will be the same as the number of tracks which in turn describes the resolution of the encoder. If 10 tracks are used, the resolution of the encoder will be $360/2^{10} = 0.35^\circ$ (William Bolton, n.d.), 2003.

d. Torque sensor

When the driver applies torque on the steering wheel, the torsion bar is twisted. Optical encoders on each end of the torsion bar measure the angular difference and combined with the torsion bar stiffness, the torque can be calculated together with steering wheel angle (“Automobile. Electr. Electron. Syst.,” 2017).

Some torque sensors used in the electric power steering system utilize the magneto resistive principle, where rotation of a magnet in relation to the sensor creates a change in magnetic field.

The magneto resistive element changes resistance when the field direction changes, which in turn can be interpreted as measured torque (Christiansen et al., 2020).

3.3 Methods

For the accomplishment to control the tire angle of the wheel the following methodologies have been followed:

1. The information is gathered and surveyed from related works and various techniques which are literature, reading books, journals, publications, documents on related areas and interviewing mechanic from garage.
2. After analyzing all of the resources, the next step is to complete the mathematical modeling for the steer by wire (SBW), which is the foundation of this thesis.
3. From mathematical model the Simulink of the system is developed for steering wheel and front wheel in addition one Simulink model for the both of them as one system in MATLAB/Simulink 2021a.
4. Depending on the mathematical model the effective controller is designed and modelled for the steering system.
5. Parameters of the controller are tuned using different optimization algorithms (GWO and GA).
6. Performance evaluation and discussed the result.
7. Analyze the design with MATLAB/Simulink simulation. In general, the method followed throughout the research can be summarized in the following flow chart of Figure 3.4.

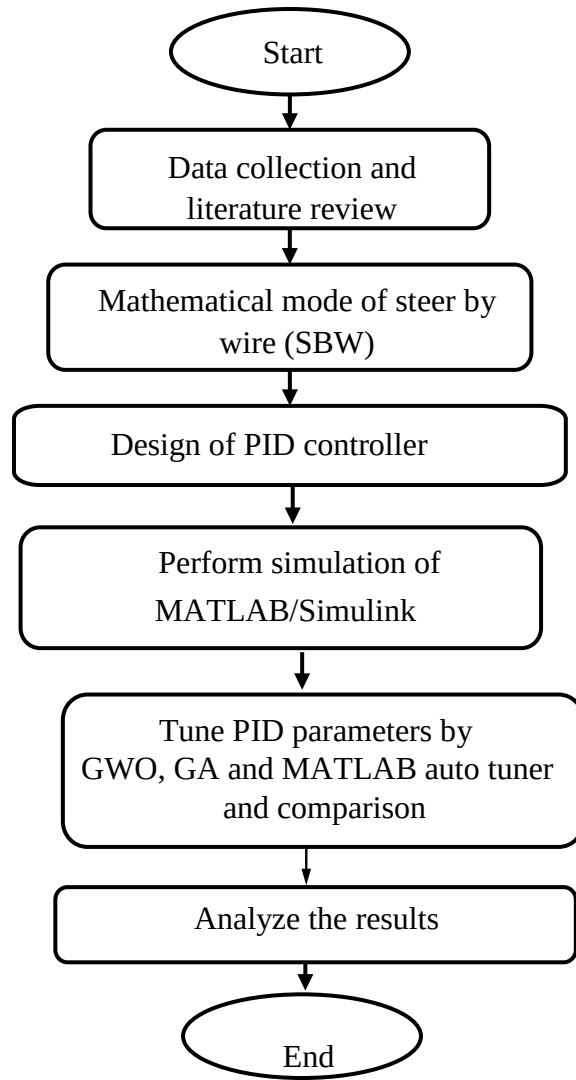


Figure 3.4: Work flow.

3.4 Modeling of the steer-by-wire system

The steering system components will be mathematically modelled using Newton's law to drive the dynamic equation for wheel angle displacement about the kingpin axis. The driver input torque T_{driver} , at the steering wheel is the primary external input of the steering systems, and the wheel rotational angles are the desired outputs. The mechanical structure of the SBW system (H. Wang et al., 2014b) is shown in Figure 3.5, where we can see that the SBW system can be divided into two separate blocks: the steering wheel block and the front wheel block. The steering wheel block consists of a steering wheel, a steering wheel angle sensor, and a steering wheel feedback

motor. The front wheel block is made up of an assembly of a steering motor and a gear head, a pinion angle sensor, a rack and pinion gearbox, and two front wheels.

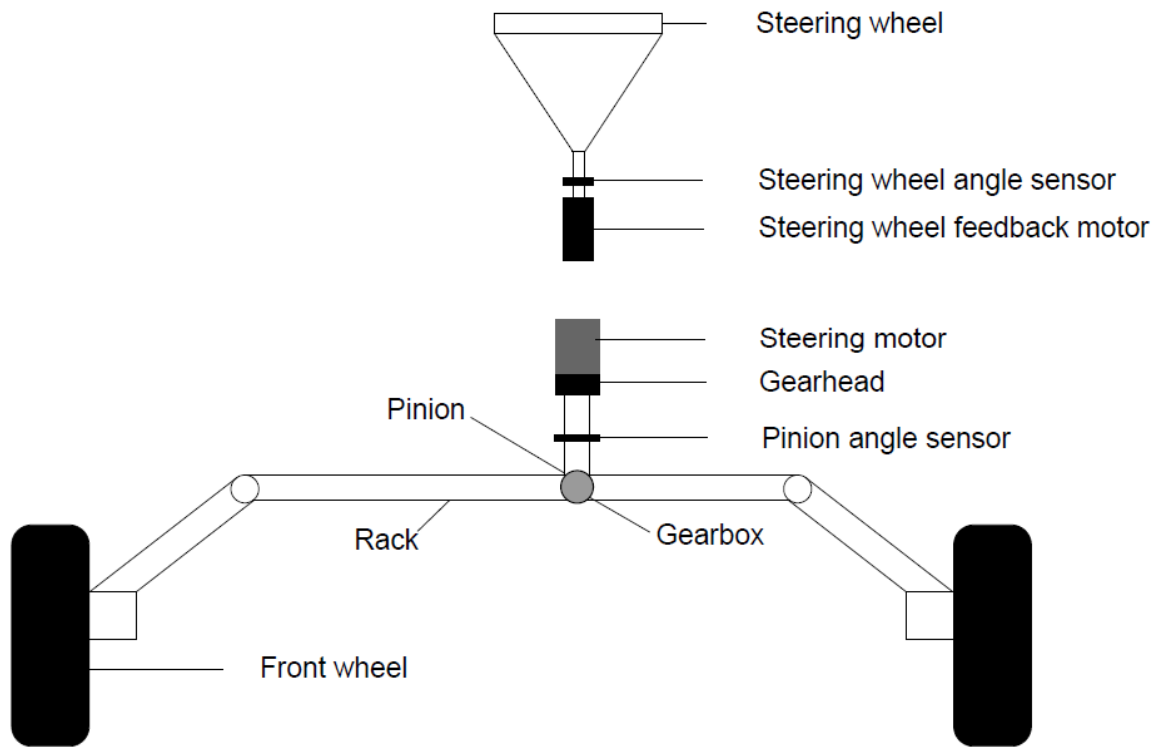


Figure 3.5: The structure of the SBW system (H. Wang et al., 2014b).

3.4.1 Steering Wheel Model

The function of the steering wheel feedback motor is to provide a feedback torque to the driver such that the driver can have the feeling of the interactions between the front wheels and the various road surfaces during driving. On the other hand, the steering motor produces a steering torque to steer the front wheels through the gear head, the rack and pinion gearbox, and the steering arm, thus ensuring the steering of the front wheels can track the rotation of the steering wheel closely (Muhammad et al., 2015).

The steer-by-wire system is comprised of the driver interface and the directional control assembly. The **steering wheel subsystem** has been modeled as shown in Figure 3.6).

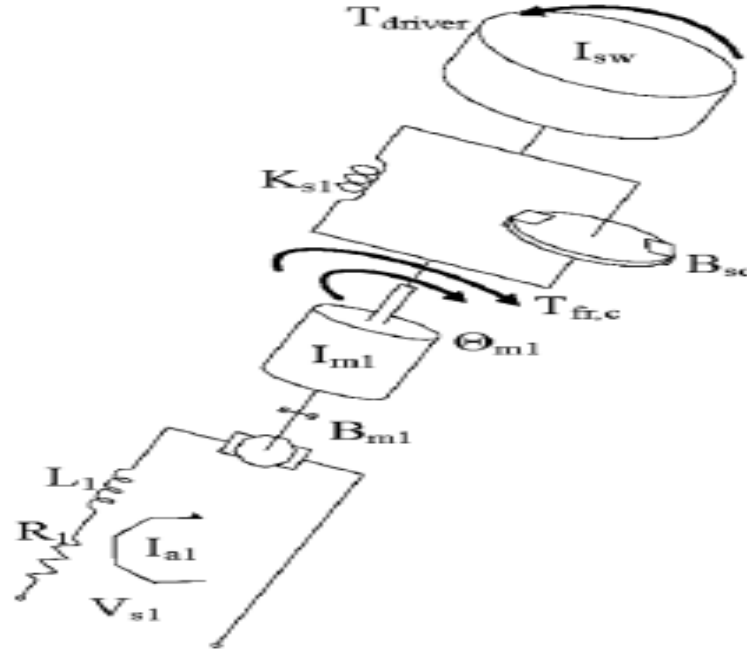


Figure 3.6: Steering wheel system diagram (Zaidi et al., 2017)

The mathematical equations of the steering wheel system are written as follows.

Steering wheel angle:

$$\ddot{\theta}_{sw} = \frac{1}{J_{sw}} [T_{driver} - T_{fr,c} - B_{sc}\dot{\theta}_{sw} - K_{s1}\theta_{sw} + B_{sc}\dot{\theta}_{m1} + K_{s1}\theta_{m1}] \quad (3.1)$$

Steering motor angular displacement:

$$\ddot{\theta}_{m1} = \frac{1}{J_{m1}} [T_{m1} - B_{m1}\dot{\theta}_{m1} - K_{s1}\theta_{m1} - B_{sc}\dot{\theta}_{m1} + K_{s1}\theta_{sw} + B_{sc}\dot{\theta}_{sw}] \quad (3.2)$$

Current of steering Motor:

$$\frac{dI}{dt} = \frac{1}{L_1} [-R_1 I_{a1} - K_{b1}\dot{\theta}_{m1} + V_{s1}] \quad (3.3)$$

Figure 3.6 shows the steering wheel diagram. In steering wheel system, the input to the system is the steering angle, θ_{sw} and driver torque, T_{driver} . While torque friction, $T_{fr,c}$ reacted as a disturbance. The output of the system is the steering motor current, I_{a1} and steering motor angular displacement, θ_{m1} .

Table 3.1: Steering wheel subsystem parameter

Parameter	Description	Value	Unit
B_{m1}	Steering motor damping	1	Nm/(rad/s)
K_{sm}	Steering motor torque constant	2	Nm/rad
J_{sw}	Steering Lumped inertia	0.0079	kgm ²
R_1	Motor electrical resistance (SM)	5.64	ohm
L_1	Motor electrical inductance (SM)	0.017	H
J_{m1}	Motor moment of inertia	0.0021	kgm ²
V_{s1}	Voltage source	12	V
B_{sc}	Steering column damping	0.136	Nm/(rad/s)
K_{b1}	Steering motor emf	0.353	V-s/rad
K_{s1}	Lumped torque stiffness (SM)	3500	Nm/rad
T_{m1}	Torque of steering motor	[0, 2]	Nm
T_{dr}	Torque of driver	[0, 4]	Nm
T_{frc}	Torque of friction	Random noise	Nm
θ_{sw}	Steering angle	-	degree
θ_{m1}	Angular displacement of steering motor	-	degree
I_{a1}	Current of steering motor	-	ampere

$$\ddot{\theta}_{m2} = \frac{1}{J_{m1}} [-B_{m2}\dot{\theta}_{m2} - K_{s2} \left(\theta_{m2} - \frac{y_r}{r_p} \right) + T_{m2}] \quad (3.5)$$

Where, $T_{m2} = K_{\tau 2} I_{a2}$. The armature current or front motor current I_{a2} may be expressed as

$$\frac{dI_{a2}}{dt} = \frac{1}{L_2} (-R_2 I_{a2} - K_{b2} \dot{\theta}_{m2} + V_{s2}) \quad (3.6)$$

And the front tire angle dynamics is

$$\ddot{\delta}_f = \frac{1}{J_f} [-k_{lf} (\delta_f - \frac{y_r}{r_L}) - T_{fr.kp} - B_{kp} \dot{\delta}_f + T_a] \quad (3.7)$$

Where the parameter name is listed in Table below.

Table 3.2: Front wheel subsystem parameter

Symbol	Description	Value	Unit
J_{m2}	Motor moment of inertia	0.0079	kgm ²
B_{m2}	Motor damping	1	Nm/(rad/s)
R_2	Motor electrical resistance (FM)	5	ohm
L_2	Motor electrical inductance (FM)	0.002	H
K_{s2}	Motor torque stiffness	3500	N/m
K_{fm}	Motor constant	2	Nm/rad
B_r	Rack damping coefficient	25	Nm/(rad/s)
B_{kp}	King pin damping coefficient	30	Nm/(rad/s)
K_{lf}	Rack linkage stiffness	26000	Nm/rad
r_p	Pinion gear radius	0.035	m
δ_f	Offset of king pin axis	0.3	m
m_r	Mass of rack	2	kg

y_r	Rack displacement	-	m
V_{s2}	Front motor voltage	240	V
δ_f	Front tire angle	-	degree
θ_{m2}	Angular displacement of front motor	-	degree
T_{m2}	Torque of front motor	-	Nm
I_{a2}	Current of front motor	-	ampere
T_a	Self-aligning torque	-	Nm
$F_{fr,r}$	Rack frictional force	9	N
$T_{fr.kp}$	King pin torque friction	2	Nm

3.6 Force Feedback Torque Estimation Control Algorithm

A Steer by Wire system, in which the steering column is removed, allows for active lateral control of the vehicle because the driver can command the steering system individually. Instead, two actuators (see Fig. below) must be fitted in the steering system to service the steering column's functions (Fankem & Müller, 2014). One to recreate the driver's steering feel, and the other to track the entire steering angle received from the driver.

Due to the absence of a mechanical column shaft in the SBW system, it was previously recognized that the force feedback torque for driver steering sense to be artificially generated. Furthermore, the proportion of steering feel obtained should be comparable to that of a traditional steering system. As a result, the steering wheel in the SBW system with the motor actuator is utilized to generate the steering feel by controlling the overall feedback torque speed and changing reactive torque to improve the drivers steering feel. The steering wheel reactive torque motor is controlled using the PID control approach.

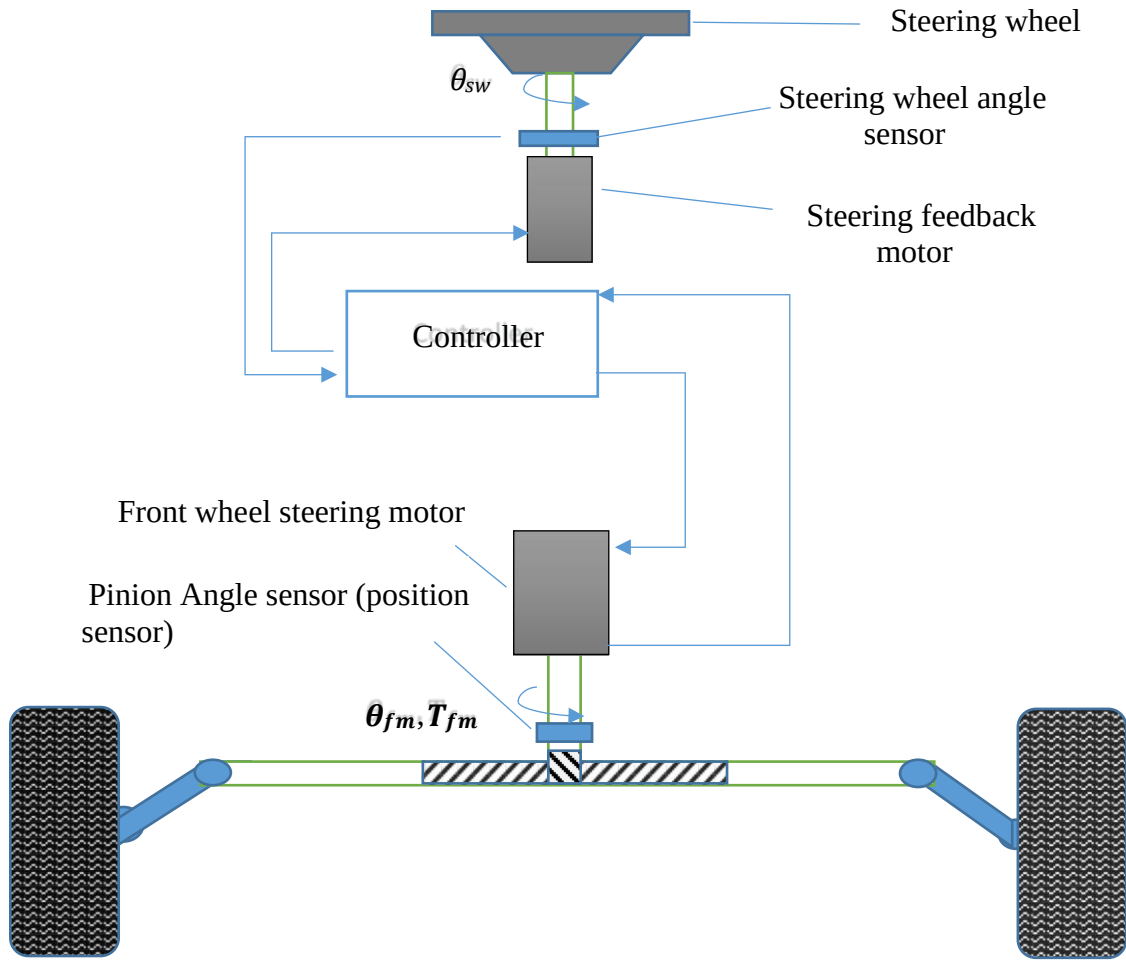


Figure 3.8: Vehicle steer by wire control system diagram (Fankem & Müller, 2014).

The self-aligning torque (T_a) functions as an input disturbance to the front axle system to demonstrate the influence of the tire on the road surface.

The total self-aligning torque can be obtained as follows:

$$T_a = (t_p + t_m)F_{l,f}(\alpha_f) \quad (3.8)$$

The overall force feedback torque to the steering wheel system is stated as follows, using the proposed control algorithm:

$$T_a = -C_f(t_p + t_m) \left[\beta + \frac{l_{fr}}{v} - \delta_f \right] \mu \quad (3.9)$$

Where μ is coefficient for road dry condition (0.75 for this thesis), pneumatic trail (t_p) and mechanical trail (t_m). On the other hand, any change of the road surface could change the feedback torque magnitude of the front axle motor.

At a small slip angle, the lateral force is linearly related to the tire slip angle α_f as shown in Figure 2.4 and can be modeled as follows:

Table 3.3: Hyundai Ioniq Electric SE 2021

Symbol	Description	Value	Unit
l	Length of the vehicle	4.470	m
w	Wheel Track (width)	1.821	m
H	Total height of the vehicle	1.476	m
L	Wheel base	2.700	m
h	Ground clearance	0.150	m
m	Gross vehicle weight	1,969.952	Kg
C_f	Front cornering stiffness	50000	N/rad
C_r	Rear cornering stiffness	50000	N/rad
l_f	Length from center front wheel to C.O.G vehicle	1.2	m
l_r	Length from center rear wheel to C.O.G vehicle	1.49	m
I_s	Inertia of vehicle	2149	Kgm ²
V	Speed of vehicle	–	Km/h
F_{yf}, F_{yr}	Front and Rear tire lateral force	–	Nm
α_f, α_r	Front and Rear tire slip angle	–	Nm

3.6.1 Generating of steering feel

By mechanically decoupling the wheel from the road wheels, steer-by-wire eliminates the hand wheel's mechanical feel. A study conducted by (Liu & Chang, 1995) revealed that this design feature can improve a driver's steering task. According to Gordon, steering torque feedback is the most requested input by drivers. Modern vehicles require a good steering feel to perform their intended function. This is because the feel of the steering wheel is very important to drivers. A good steering feel in steer by wire is created by carefully selecting the various components of a vehicle's system

Another way of making the steering feel on the steer by wire vehicle is by creating the steering motor torque feedback on to the driving. In this study, (Nguyen & Ryu, 2009) demonstrated that the steering motor current can generate feedback using hardware in the loop simulator. The results of the study revealed that a steering motor current and a torque map can generate a steering feel. However, this technique is limited to a realistic steering feel and cannot be changed easily in software. Another way to create a feel for a steering system is to use a low fidelity model. This model can be derived by taking a spring model and adding an abstract physical system. It can be used to simulate the physical system.

Low-fidelity models, while simple to build, are unable to capture all of the critical aspects of steering feel, such as power assist and steering "heaviness." Higher fidelity models have been utilized in simulators to capture more elements of steering feel than low fidelity versions. Though higher fidelity models can capture more aspects of steering feel, adjusting becomes more difficult as the number of model parameters increases. As a result, processes such as frequent subjective human evaluations are used to validate data are required (U. B. Mandhata et al., 2012).

Today, the driving sensation of traditional vehicles varies greatly. Steer by wire vehicles should be no different. Therefore, a higher fidelity steering feel model is required, which can produce good changes in steering feel. However, as the fidelity of the models increases, it becomes more difficult to adjust these models to get the desired feel. Therefore, an acceptable level of fidelity of the steering model must be found. The model must be complex enough to capture all the steering sensations that modern drivers care about, such as "weight", power assistance, "stiffness", etc. But it should be as simple as intuitively adjustable. This issue studies the industry's objective steering

feel performance indicators as a means of determining steering feel that modern drivers consider important. Then, this topic recommends capturing these basic components using an acceptable fidelity steering sensory model and making changes using an intuitive set of touch options. Then, in this topic, steering-fill model with acceptable fidelity to capture these key factors is prepared, while intuitively adjusting to a small set of parameters. This topic starts with a simple steering feel model that captures the changes that occur as a result of the torque acting on the tires, power assist, and the inherent inertia and damping of the wired steering system. Next, we introduce the industry goals for measuring sensory steering performance as a means of understanding and quantifying sensory steering. These performance indicators depend not only on the steering model, but also on the driving force of the vehicle. A simple vehicle dynamics simulation can be used to determine the main set of parameters for the steering model, which can adjust these measurements to indicate the need. Defined performance measurements achieved by dynamic vehicle simulations based on experimental data can generally be replicated to a real steering-by-wire car (Balachandran & Gerdes, 2015).

3.6.2 Artificial Steering Feel

A conventional steering system is mechanically connected to a steering wheel road wheel as shown below. Steer-by-wire vehicles are mechanically separated from the steering wheel road wheel. Steering commands from the driver are sent electronically to the motor, which causes the motor to actuate the road wheel. This mechanical decoupling removes much of the steering feel normally present on conventional vehicles

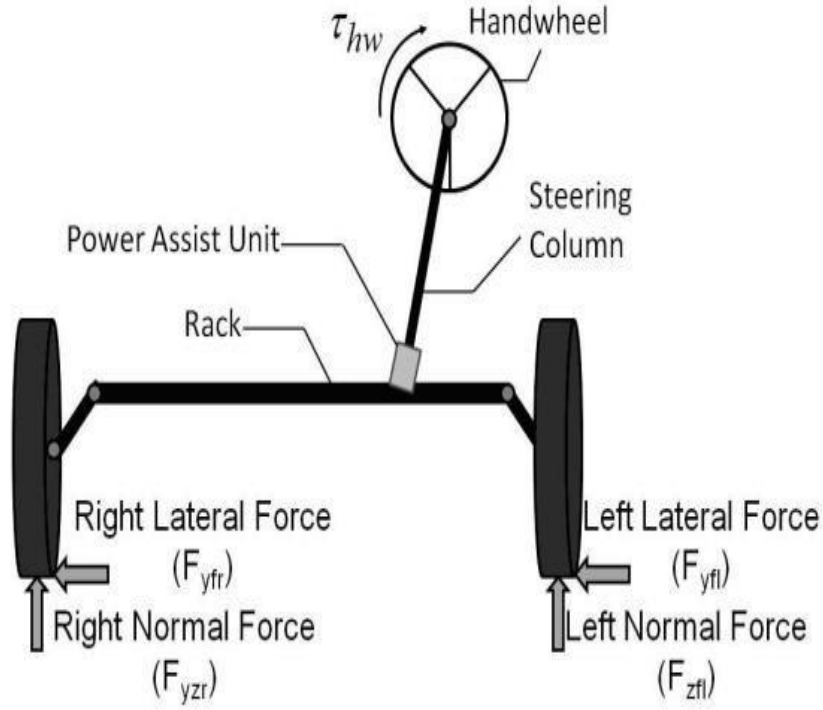


Figure 3.9: Conventional steering system (Balachandran & Gerdes, 2015).

Steering feel can be artificially created in steer-by-wire vehicles using a force feedback (FFB) steering system, as shown in Figure 3.9. For this system, the motor torque (T_m) and the inherent steering system dynamics as determine the steering wheel torque (T_{sw}) felt by the driver:

$$\tau_{hw} = \tau_{motor} + J_{system}\ddot{\delta}_{hw} + b_{system}\dot{\delta}_{hw} \quad (3.10)$$

When the steering wheel FFB motor torque (τ_{motor}) is commanded, the intrinsic system inertia (J_{system}) and system damping (b_{system}) are found in the identification of the mechanical system and the steering wheel angle (δ_f) becomes driver input.

3.6.3 Conventional Steering Feel

In steer by wire to develop the artificial steering feel of a vehicle, the FFB steering system needs to feel like a traditional operating system. Conventional steering vehicles have three main torques that make up the steering feel. They are:

- Tire Moment
- Torque by Inertia Damping

- Torque by Power Assist

By weighted sum of these torques, the steering feel felt by the driver can be obtained.

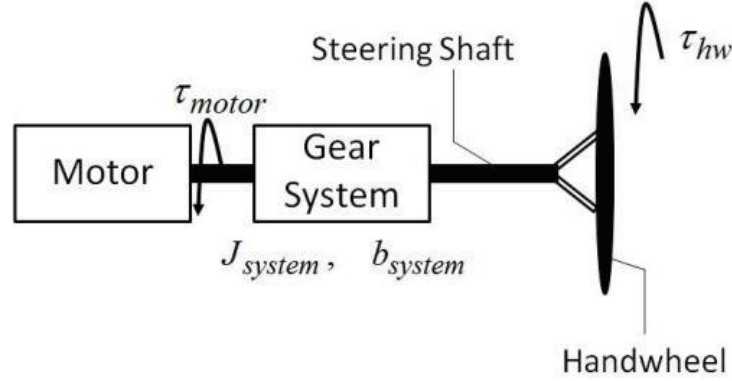


Figure 3.10: Force Feedback (FFB) steering system (Balachandran & Gerdes, 2015).

3.6.3.1 Tire Moments

Figure 3.11 shows a conventional mechanical steering system with left and right front lateral tire forces (F_{yfl}, F_{yfr}) and left and right front normal tire forces (F_{zfl}, F_{zfr}) displayed. Figure 3.10 shows the typical same suspension geometry of a conventional vehicle shown in steering axis mechanical trail (t_m) pneumatic trail (t_p), caster angle (θ_c), kingpin inclination angle (θ_k) and scrub radius (d). The moments created by the transverse and general tire forces around the steering axis form a major factor in the steering feel. The moment around the steering axis created by the lateral force of the tire is called the alignment moment and is given by the equation (Balachandran & Gerdes, 2015).

$$\tau_{align\ Moment} = -(F_{yfl} + F_{yfr})(t_m + t_p)\cos\sqrt{\theta_c^2 + \theta_k^2} \quad (3.11)$$

At greater speeds, the aligning moment produces a large self-centering torque. The jacking torque is the moment about the steer axis created by normal tire forces, and it is given by

$$\tau_{jacking\ Torque} = -(F_{zfl} + F_{zfr})d\sin\theta_k\sin\delta_{rw} + (F_{zfl} - F_{zfr})d\sin\theta_c\cos\delta_{rw} \quad (3.12)$$

Where the δ_{rw} is the road wheel angle. At low speeds, when the effect of the aligning moment is negligible, the jacking torque accounts for the majority of the self-centering effect of the steering feel. Because the steering linkages transmit the aligning moment and jacking torque to the hand wheel, these two tire moments have a considerable impact on the steering feel.

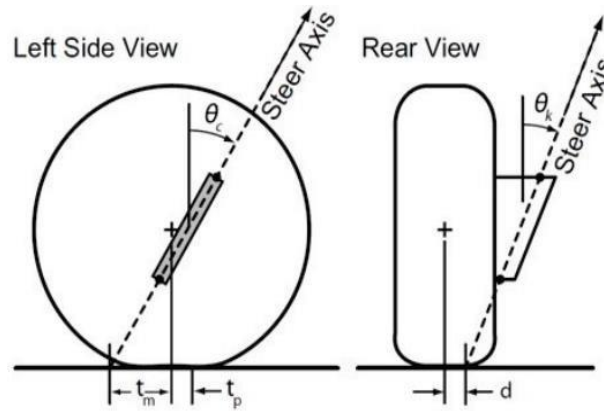


Figure 3.11: Typical suspension geometry on conventional vehicle (P. Switkes et al., 2006)

The aligning moment results in a strong self-centering torque at higher speeds. The moment about the steer axis generated by the normal tire forces is known as the jacking torque. Where the δ_f is the road wheel angle.

Design parameter of for the jacking torque is as follows in Table 3.4

Table 3.4: Steering knuckle parameter (S. Laws et al., 2005).

Parameter at zero steer	Typical value	Current design parameter
Wheel radius (R_l)	300 to 350 mm	320mm
Caster angle (θ_c)	4 to 7°	5.50
Kingpin inclination angle(θ_k)	7 to 15°	13.2°
Scrub radius (d)	-75 to 75 mm	50mm
Mechanical trail (t_m)	15 to 50mm	28mm

3.6.3.2 Torques due to inertia and damping

Figure 2.1 shows the existence of a series of mechanical connections between the hand wheel road wheels: steering column, power assist device, rack, suspension, etc. This gives the steering system its own damping and inertia. This inherent damping and inertia create an additional torque the driver will feel and forms part of the steering feel.

3.6.3.3 Torque due to Power Assist

In the modern power steering system, the driver receives an auxiliary torque corresponding to the overall front tire moment to help turn the road wheels. The difference between the total front tire moment and the driver's input torque as measured from the steering rack using a flexible torque measuring element such as a torsion bar and the torque due to the driver's input torque determines the amount of assistive torque. The larger the difference in this torque, the larger the auxiliary torque. This assistive torque also significantly displays the steering feel.

3.6.4 Creating Artificial Steering Feel

Building a steering feel model with the appropriate fidelity allows the creation of artificial steering feel on steer-by-wire vehicles. The model in this part simplify the steering feel model, which included tire moments, torques related to steering system characteristics, static friction, and a power assist model. (U. Mandhata et al., 2010). It was assumed that a torsion bar would be used. The model described in this part accounts for tire moments and torques caused by steering system parameters while simplifying the power assist model to make it more general. This more general model does not require a torsion bar windup as an input as steer-by-wire vehicles, like the one shown in this paper, need not have a torsion bar (J. Wang et al., 2019).

Based on this model, the feedback motor torque (τ_{damp}) is given equation 3.13:

$$\tau_{motor} = \tau_{damp} + \tau_{inertia} + K\tau_{assisted\ tire\ moment} \quad (3.13)$$

Where the damping torque (τ_{damp}) and the inertia torque ($\tau_{inertia}$) change the intrinsic damping and inertia of the steering system. This is explained in detail below. Tire moment gain (K) varies with different steering systems, suspension geometries and steering ratios, taking into account the transfer of moments from the tire to the steering wheel. The larger the K, the more of the assist tire moment is incorporated into the steering feel.

3.6.4.1 Damping Torque (τ_{damp})

Damping torque corrects the effect of steering-feeling unique system damping (b_{system}). Traditional vehicles have their own damping than steer-by-wire vehicles because they have a more complex steering system mechanically. Therefore, it is generally necessary to add damping torque

for the steering-by-wire system. Correcting the damping inherent in traditional vehicles is a daunting task as it involves actual hardware changes. However, using the model proposed in this section, it is much easier to correct the system attenuation and it can be done using software. Changes in intrinsic damping are created using the following model:

$$\tau_{damp} = -\Delta b \dot{\delta}_{rw} \quad (3.14)$$

3.6.4.2 Inertia Torque ($\tau_{inertia}$)

The inertia torque changes the effect of the intrinsic system inertia (J_{system}) on the steering feel. Conventional vehicles have inherent inertia than steering-by-wire vehicles for reasons such as inherent damping. The model proposed in this section makes it much easier to change the inertia of the system, which can be implemented using software. Changes in intrinsic inertia are created using the following model:

$$\tau_{inertia} = -\Delta J \ddot{\delta}_{rw} \quad (3.15)$$

3.6.4.3 Aligning Moment (τ_{align})

The force of the front tires and the resulting moment have a huge impact on the steering feel. The effect of front side tire force (F_{yf}) on steering feel is due to the alignment moment. Assuming that the caster angle (θ_c) and the kingpin inclination angle (θ_k) are small in (2.2), the alignment moment can be estimated as the product of the previous lateral tire force and the total trajectory of the vehicle as follows.

$$\tau_{align} = -F_{yf}(t_m + t_p) \quad (3.16)$$

Where t_m is the mechanical trail and t_p is the pneumatic trail of the vehicle, using small angle assumptions reduces the number of parameters required for the model.

The brush tire model proposed by Fiala and presented by Pacejka in the following form provides a useful approximation of the nonlinear relationship between tire force and slip angle (Beal & Gerdes, 2013).

$$F_y = -C_\alpha \tan \alpha + \frac{C_\alpha^2}{3\mu F_z} \tan \alpha |\tan \alpha| - \frac{C_\alpha^2}{27(\mu F_z)^2} \tan^3 \alpha \quad (3.17)$$

Here, the surface friction coefficient (μ) and the cornering stiffness of the tire (C_a) are the design parameters. Normal load (F_z) can be obtained from the mass of the vehicle.

For the sake of ease, It is assumed that the mechanical trail (t_m) is constant and the air trail (t_p) is modeled as a decreasing linear function of slip angle introduced.

$$t_p = t_{po} - \text{sgn}(\alpha_f) \frac{t_{po} C_{af}}{3\mu F_{zf}} \tan(\alpha_f) \quad (3.18)$$

Here, the pressure traces at zero front slip angle (t_{po}), surface friction coefficient (μ), and front tire cornering stiffness (C_{af}) are the design parameters. This simplicity reduces the number of tuning parameters. This alignment moment term reflects the current road conditions to the driver via steering feel. Surface friction coefficients can be obtained using the same real-time friction estimation method proposed (Judy Hsu et al., 2010). Thus, an alignment moment term is created that corresponds to the current road conditions in which the appropriate front-side tire force and pressure traces were used.

3.6.4.4 Jacking Torque (τ_{jack})

Front normal tire force (F_{zf}) affects steering feel through jack torque. When the parked driver turns the steering wheel, the jack torque effect is clearly visible. This means that the vehicle's bonnet "jacks up" (which is where the name comes from) and the hand wheel has an automatic return torque. The effect is much more pronounced at low speeds, but the alignment moment effect is even more pronounced at high speeds.

Normal Tire Force By making a reasonable assumption that the sum of is much larger than the difference, i.e. $((F_{zfl} + F_{zfr}) \gg (F_{zfl} - F_{zfr}))$ and the road wheel angle (δ_f) is small, the spring model can be approximated. This spring model provides a useful approximation of jacking torque to capture important centering effects in a simple model. A simple single spring model of Jacking Torque is:

$$\tau_{jack} = -K_{jack} \delta_{rw} \quad (3.19)$$

Here, jack torque stiffness (K_{jack}) is a design parameter.

3.6.4.5 Power Assist

In modern power steering systems, the driver receives an auxiliary torque that offsets the total moment of the front tires and assists the rotation of the road wheels. This torque affects steering opinion. Ryu and Kim demonstrated that the effect of this auxiliary torque on the synthetic steering feedback is that only a fraction of the total moment of the front tire is included in the steering feedback (Jeha Ryu & HeeSoo Kim, 2003). Using the alignment moment and jack torque equation obtained before, the total moment of the front tire can be estimated as:

$$\tau_{tire\ moment} \approx \tau_{jack} + \tau_{align} \quad (3.20)$$

Then the ratio of the total moment of the front tire felt by the driver is modeled as a weighting function (W_f) according to the front slip angle. The resulting assisted front tire total moment is:

$$\tau_{assisted\ tire\ moment} = \tau_{tire\ moment} W_f \quad (3.21)$$

When the front slip angle reduces as the magnitude of the front slip angle rises, this weighting function must have a single value, according to Ryu and Kim's analysis. When the front tire force is zero, there is no assist, and as the front tire force grows, the support level rises. When the magnitude of the front tire force surpasses a specified threshold set based on the desired power assist features, the weighting function also includes a lower limit that is read as saturation of the power assist effect. Modeling the weighting function (W_f) as a Gaussian function meets these important requirements. The weighting function (W_f) is specified as follows:

$$W_f = e^{\frac{-\alpha_f^2}{2\sigma_{ps}^2}}(1 - \gamma) + \gamma \quad (3.22)$$

Here, the front slip angle (α_f) is known, and the standard deviation (σ_{ps}) minimum weight (W_{fmin}) and maximum weight (W_{fmax}) are chosen to create the desired power steering effect. Note that $0 \leq W_{fmin} \leq W_f \leq W_{fmax} \leq 1, \forall \alpha_f$. The higher the weight (W_f), the more the tire's total moment is included in the steering feel. Therefore, as the slip angle increases and the tire force increases, the W_f decreases and a very small fraction of the total tire force is included in the steering feel. This

reproduces the power assist effect. Zero weight ($W_f = 0$) means that only the damping torque and inertia torque are included in the steering feel, without the total moment of the tire. W_{fmax} are design parameters that are usually set to 1. This indicates that, in the absence of the power assist effect, the steering feel tire moment effect is perfectly integrated, as in a vehicle with purely manual steering.

3.7 Controller Design

PID controllers are the most commonly used controllers in process industries. About 90% of industrial loops use PID controllers. This is because of its simple structure, easy implementation, robust nature and less number of tuning parameters (Chopra et al., 2014). The time-domain equations of the PID controller are shown below in Equations (23) and (24). The final PID algorithm is of the form, where "u" represents the controller output.

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \quad (3.23)$$

Where, $u(t)$ is the control signal, $e(t)$ the error signal which is the difference between the reference signal $r(t)$ and the system output $y(t)$. K_p , K_i and K_d are the proportional gain, the integral gain and the derivative gain respectively. These are the parameters to be tuned.

3.8 Structures of PID controllers

PID controllers commonly use parallel and series structures:

Parallel Type: Proportional P, integral I, or derivative D actions occur in distinct equation terms in this form, and the sum is formed by their combined effect. Each parameter in this type is independent of the others, and the equivalent control law is written as:

$$u(t) = K_c \left(e(t) + \frac{1}{T_i} \int e(t) dt + T_d \frac{de(t)}{dt} \right) \quad (3.24)$$

Where, the proportional gain is $K_p = K_c$, integral time is T_i and $K_i = K/T_{ic}$, derivative time is T_d and $K_d = K_c T_d$. This is also known as an ideal representation.

Series Type: The pneumatic and analog electrical circuit features influence the series or interactive equation the most. Changes in K_c affect all three actions, just as they do in an ideal PID equation, but proportional action is influenced by both derivative and integral constants (Borase et al., 2020).

This type has the following control law:

$$e_1(t) = e(t) + T_d \frac{de(t)}{dt} \quad (3.25)$$

$$u(t) = K_c(e_1(t) + \frac{1}{T_i} \int e(t)dt) \quad (3.26)$$

3.9 Role of PID Controller

PID controller maintains the error between the process variable and the set point zero by closed-loop operations. It is the composition of proportional, integral, and derivative actions that are explained below. A proportional controller (K_p) reduces the rise time and lowers the steady-state error, but never completely eliminates steady-state error. While an integral control (K_i) will eliminate the steady state error, it can increase the transient response. The effect of a derivative control (K_d) is to improve the system's stability, reduce overshoot, and improve the transient response.

Proportional action (P): It gives a result that is relative to current error $e(t)$. When used alone, P-action requires biasing or manual reset. This is due to the fact that it never achieves the steady-state condition. It provides stable operation while maintaining the steady-state error.

Integral action (I): Due to the restriction of P-action where there continuously exists an offset between the method variable and set point, I-action is required, which provides the necessary activity to resolve the steady-state error. When a negative error occurs, integral control reduces its output. It slows down the system's response time and affects its stability. The response speed is enhanced by lowering the integral gain, K_i .

Derivative action (D): I-action does not have the capability to predict error behavior in the future. So, it reacts normally once the set point is changed. D-action solves this problem by predicting the error's future behavior. It increases system response by providing a kick start for the output (Rigelsford, 2001).

3.10 Objective Functions

The most important step in using any optimization technique is to select the objective functions that will be used to estimate each population's fitness (particle). Optimization of a controller is accomplished by minimizing the objective function. The three commonly used objective functions in tuning controller parameters are the integral of absolute error (IAE), the integral of time multiplied absolute error (ITAE), and the integral of squared error (ISE) which are based on the error (Krohling & Rey, 2001).

$$IAE = \int_0^t |e(t)| dt \quad (3.27)$$

$$ITAE = \int_0^t t|e(t)| dt \quad (3.28)$$

$$ISE = \int_0^t e^2(t) dt \quad (3.29)$$

Each of the above assess is calculated over some interval of time $0 \leq t \leq t_f$ where t_f is a time long enough for the error to settle down. These performance criteria have advantages as well as disadvantages. For example, ISE tuning makes large errors larger and small errors smaller and often leads to a fast response with low amplitude oscillation. IAE does not add any weight to the errors and tends to provide slower response than ISE tuning (Al-Mayyahi et al., 2016). ITAE imposes small time penalty for the initial large error and gives higher time weight to the absolute error at later times due to the effect of time penalty, ITAE tuning produces an initial slow response. Another disadvantage of these three methods is that they tune the controller for the control input to be excessively large in order to quickly reduce the error. This causes saturation in the actuator and can ultimately lead to integrator wind-up problems (Sahib & Ahmed, 2016).

Therefore, in this work, not only the time integral of absolute error is employed as a part of the performance index to achieve the satisfactory dynamic characteristics in the transition process but also the absolute controlled variable is adopted to avoid the large control input.

3.11 Tuning of the Controllers

3.11.1 Grey Wolf Optimization (GWO)

Grey wolf belongs to Canidae family and mostly prefer to live in a highly organized pack. The average group size is 5–12 members, and they have a very tight social dominating hierarchy, as

shown in the Figure 3.12. In 2014, Mirjalili introduced the GWO algorithm; a search and optimization method that replicates grey wolf hunting. This strategy is used to recreate the social order and hunting behavior of wild grey wolf packs. Alpha, beta, delta and omega wolves are the four various ranks of wolves in a pack.

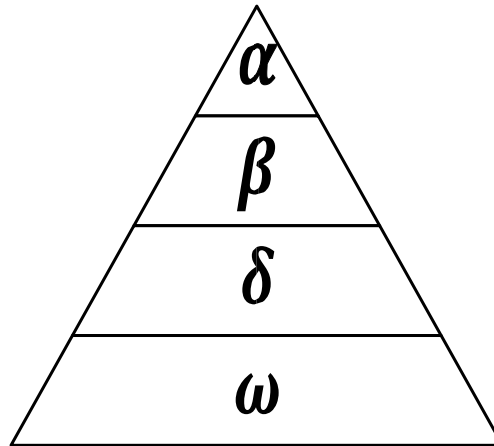


Figure 3.12: Hierarchy of grey wolf (Mirjalili et al., 2014).

The alpha is the leader of the pack and responsible for making decisions about hunting, sleeping place, time to wake, and so on. The alpha's decisions are dictated to the pack also alpha follows the other wolves in the pack. In gatherings, the entire pack acknowledges the alpha by holding their tails down. This demonstrates that a pack's organization and discipline is far more crucial than its strength. In terms of pack management, the Alpha Wolf is the best (Mech, 1999).

The beta is the second level in the grey wolf hierarchy, and it assists the alpha in making decisions and other pack tasks. In the event that one of the alpha wolves dies or becomes very old, the beta wolf is generally the best candidate to become the alpha. The beta wolf serves as an advisor to the alpha, reinforcing the alpha's directives across the pack and providing feedback.

Delta wolves also called subordinate. Scouts are in responsible of checking up on the territory's borders and alerting the pack if there are any dangers. Sentinels guard and ensure the pack's safety. When it comes to hunting prey and supplying food for the pack, hunters assist the alphas and betas. Finally, the caretakers are responsible for caring for the weak, ill, and wounded wolves in the pack.

The lowest ranking grey wolf is omega. The omega plays the role of scapegoat and always have to submit to all the other dominant wolves. They are the last wolves that are allowed to eat in addition in some cases the omega is also the babysitters in the pack.

The search optimization method is based on grey wolf hunting actions and sorting solutions by group hierarchy, many studies (Padhy & Panda, 2021), (Teng et al., 2019), (Precup et al., 2017) have been published that examine the GWO algorithm in detail. Group hunting is another fascinating social characteristic of grey wolves, in addition to their social hierarchy. The main phases of grey wolf hunting are as follows:

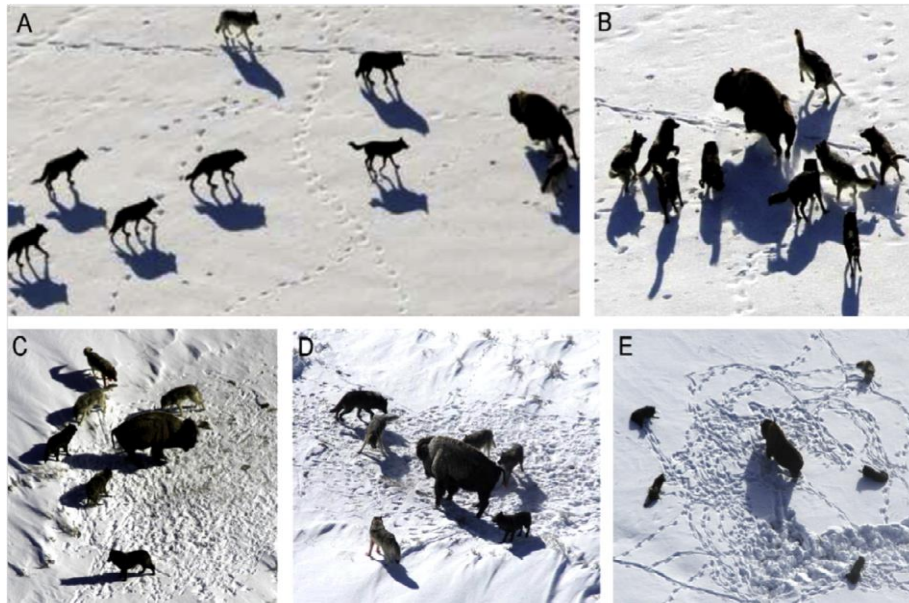


Figure 3.13: Hunting behavior of grey wolves (Muro et al., 2011)

(A) chasing, approaching, and tracking prey (B–D) pursuing, harassing, and encircling (E) stationary situation and attack.

In this work this hunting technique and the social hierarchy of grey wolves are mathematically modeled in order to design GWO and perform optimization.

3.11.1.1 Mathematical model of grey wolf algorithm

I. Social hierarchy

The fittest solution is alpha (α), the second and third best possible solutions are beta (β) and delta (δ), respectively, to mathematically describe the social hierarchy of wolves when developing GWO. All of the remaining possible solutions are considered to be omega (ω). In the GWO algorithm the hunting (optimization) is guided by α , β , and δ . The ω wolves follow these three wolves.

II. Encircling prey

After tracking, chasing, and approaching the prey grey wolves encircle a prey during the hunt. A mathematically model of an encircling behavior grey wolf is given below.

$$\vec{D} = |\vec{C} * \vec{X}_p(t) - \vec{X}(t)| \quad (30)$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A} * \vec{D} \quad (31)$$

Where t indicates the current iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\vec{X}_p$ is the position vector of the prey, and $\vec{X}$ indicates the position vector of a grey wolf.

The vectors $\vec{A}$ and $\vec{C}$ are calculated as follows:

$$\vec{A} = 2\vec{a} * \vec{r}_1 - \vec{a} \quad (32)$$

$$\vec{C} = 2 * \vec{r}_2 \quad (33)$$

Where components of $\vec{a}$ are linearly decreased from 2 to 0 over the course of iterations and $\vec{r}_1, \vec{r}_2$ are random vectors in $[0, 1]$. By altering the values of $\vec{A}$ and $\vec{C}$, other places surrounding the best search agents can be reached with respect to their current position.

III. Hunting

The alpha guide the hunting, the beta and delta might also participate in hunting occasionally. So, in order to mathematically model grey wolf hunting behavior, we assume that the alpha (best candidate solution), beta, and delta have a better understanding of possible prey locations. As a result, we preserve the top three best solutions so far and require the other search agents (including the omegas) to update their places in accordance with the best search agents' positions. In this regard, the formulas listed below are proposed.

$$\vec{D}_\alpha = |\vec{C}_1 * \vec{X}_\alpha - \vec{X}|, \quad \vec{D}_\beta = |\vec{C}_2 * \vec{X}_\beta - \vec{X}|, \quad \vec{D}_\delta = |\vec{C}_3 * \vec{X}_\delta - \vec{X}|, \quad (3.34)$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1 * (\vec{D}_\alpha), \quad \vec{X}_2 = \vec{X}_\beta - \vec{A}_2 * (\vec{D}_\beta), \quad \vec{X}_3 = \vec{X}_\delta - \vec{A}_3 * (\vec{D}_\delta), \quad (3.35)$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (3.36)$$

In a 2D search space, Figure 3.14 illustrates how a search agent adjusts its position according to alpha, beta, and delta. The ultimate position would appear to be at random within a circle defined by the positions of alpha, beta, and delta in the search space. In other words, alpha, beta, and delta compute the prey's location, while other wolves update their positions at random around the prey.

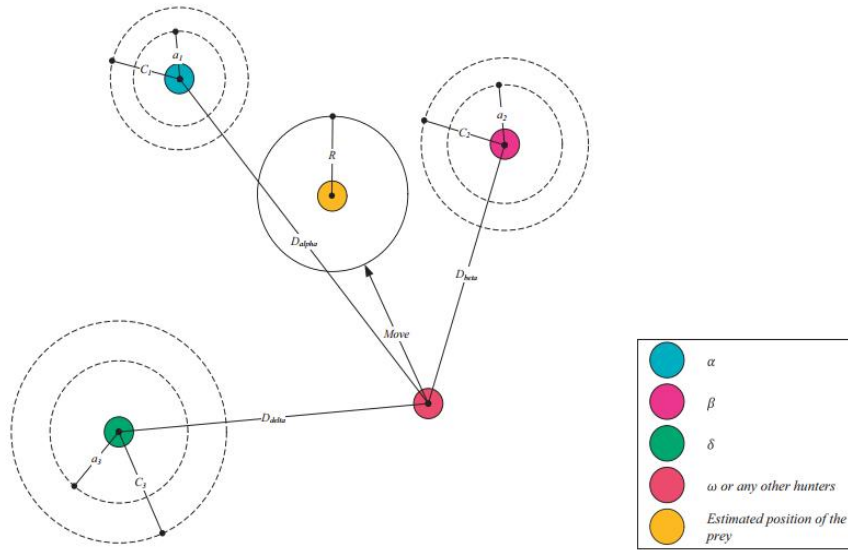


Figure 3.14: Position updating in GWO (Mirjalili et al., 2014)

IV. Attacking prey (exploitation)

Grey wolves finish the hunt by attacking the prey when it stops moving. In order to mathematically model approaching the prey we decrease the value of $\vec{a}$. Note that the fluctuation range of $\vec{A}$ is also decreased by $\vec{a}$. In other words $\vec{A}$ is a random value in the interval $[-2\alpha, 2\alpha]$ where α is decreased from 2 to 0 over the course of iterations. When random values of $\vec{A}$ are in $[-1, 1]$, a search agent's next position can be anywhere between its current position and the position of the prey. When $|A| < 1$ the GWO algorithm allows its search agents to update their position based on the location of the alpha, beta, and delta; and attack towards the prey, forcing the wolves to attack towards the prey.

V. Search for prey (exploration)

Grey wolves search mainly using the alpha, beta, and delta positions. They separate to find for prey and then converge to attack prey. We use A with random values higher than 1 or less than -1

to force the search agent to diverge from the prey in order to mathematically simulate divergence. This encourages exploration and allows the GWO algorithm to search the entire globe.

The pseudo code of the GWO algorithm is presented in Fig. 3.15

```

Initialize the grey wolf population  $X_i$  ( $i = 1, 2, \dots, n$ )
Initialize  $a$ ,  $A$ , and  $C$ 
Calculate the fitness of each search agent
 $X_\alpha$  = the best search agent
 $X_\beta$  = the second best search agent
 $X_\delta$  = the third best search agent
While ( $t < \text{Max number of iterations}$ )
    for each search agent
        Update the position of the current search agent
    end for
    Update  $a$ ,  $A$ , and  $C$ 
    Calculate the fitness of all search agents
    Update  $X_\alpha$ ,  $X_\beta$  and  $X_\delta$ 
     $t = t + 1$ 
end while
return  $X_\alpha$ ,

```

Figure 3.15: The GWO algorithm's pseudocode.

To see how GWO is theoretically able to solve optimization problems, some points may be noted:

The proposed social hierarchy assists GWO to save the best solutions obtained so far over the course of iteration.

The proposed encircling mechanism defines a circle-shaped neighborhood around the solutions which can be extended to higher dimensions as a hyper-sphere.

The random parameters A and C assist candidate solutions to have hyper-spheres with different random radii.

The proposed hunting method allows candidate solutions to locate the probable position of the prey.

Exploration and exploitation are guaranteed by the adaptive values of a and A.

The adaptive values of parameters a and A allow GWO to smoothly transition between exploration and exploitation.

With decreasing A, half of the iterations are devoted to exploration ($|A| \geq 1$) and the other half are dedicated to exploitation ($|A| < 1$).

The GWO has only two main parameters to be adjusted (a and C).

3.11.2 Genetic Algorithm (GA)

Genetic Algorithms (GAs) are a randomly determined global search method that imitate the process of natural evolution. The GA starts with no knowledge of the correct solution and depends entirely on responses from its environment and evolution operators such as reproduction, crossover and mutation to arrive at the best solution. By starting at several independent points and searching in parallel, the algorithm avoids local minima and converging to sub optimal solutions (Q. Wang et al., 2003).

The GA starts by initializing a population with a random population consisting of 20-100 individuals. The accuracy and time to convergences are affected by the scale of the original population. Small populations represent small parts of the search space; the time for generation is short since further generations are needed to converge. A large population distribution occupies a large portion of the search space, necessitating fewer generations. The time per generation, on the other hand, is increased (Tinham, 2009).

The next step after population initialization is fitness calculation. An objective function helps to determine the fitness value of all chromosomes in each generation. The fitness evaluation step in GA decides how good the solution is concerning the objective function. Generally, it is the guide

to an optimal solution. After the fitness evaluation, the selection operation determines the following population based on the fitness value.

The selected group is called the mating pool. In the crossover, the stage focuses on swapping certain parts of the mating pool strings to capture the good details of old chromosomes create new ones. Each pair of strings is subjected to the following crossover:

A crossover point k is chosen randomly within the length L of the chromosome. Swapping of the tail parts between $k+1$ and L results in two new sequences (Suthar & Gadit, 2017). A crossover operation takes place with probability. Having the likelihood of 0 means that the offspring will be exact copies of their parents. A chance of 1 means that each generation will be composed of entirely new offspring. At random, the freshly replicated strings in the mating pool are paired in the single-point crossover. For maintaining genetic diversity from generation to generation, one or more genes in a chromosome are changed from their initial state; this stage is known as mutation. The mutation operation alters each gene with a low probability because a high mutation rate destroys fit genes this series of operations is repeated until the stop condition is satisfied.

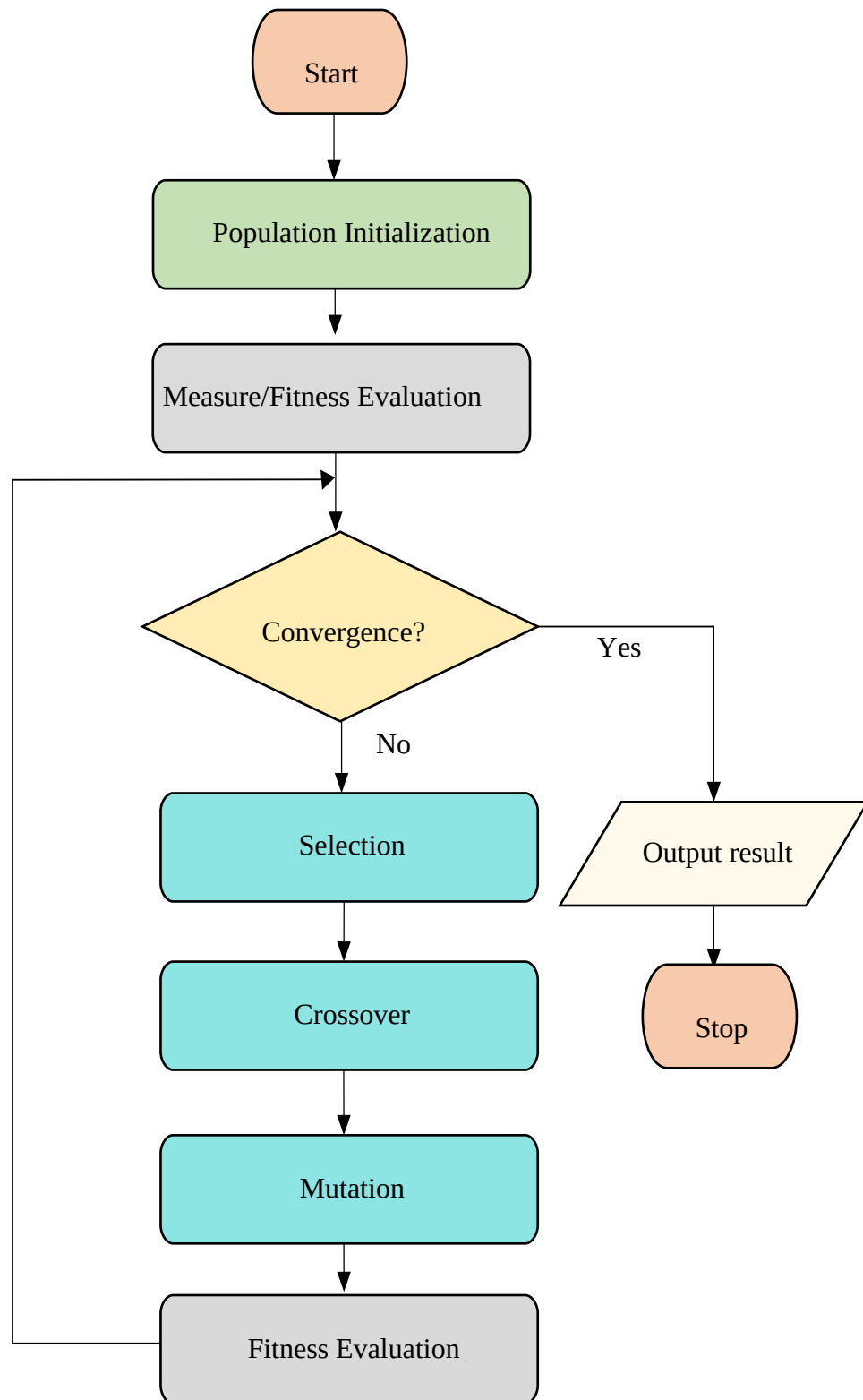


Figure 3.16: Basic structure of a GA

The pseudo code of the GA is presented in Figure 3.17

```
Initialize parameter  
Create initial population  
While ( $t < \text{Max number of iterations}$ )  
    Calculate the value of fitness for individual in the population using (ITEA)  
    For i: max iteration  
        Select individuals for the new population –selection  
        Perform cross-over operation  
        Perform mutation of individual  
        Evaluate individuals  
        Replace old population with the new one  
    end  
     $t=t+1$   
end
```

Figure 3.17: Pseudo code of the GA.

3.12 SBW System Structure

The steer by wire mathematical model is designed based on Newton's 2nd law of motion. This designed model is a nonlinear system. In order to control this system, it needs an appropriate controller design a PID controller. As shown in Figure 3.18 below, the input angle is the steering angle used for direction control (turn left or turn right) of the vehicle. This output angle is compared with the reference angle and fed to the controller (PID). This controller is tuned using optimization algorithms (GWO and GA) and MATLAB/SIMULINK auto tuner in order to produce a satisfactory result. The controller output applied to the BLDC motor (actuator) to produce appropriate torque that derives the vehicle direction control (turn left or right).

Figure 3.18 and Figure 3.19 shows steering wheel system block diagram and the front wheel system diagram respectively. Steering angle is the input of the first system and the steering motor angular displacement, θ_m is considered as the output of the system which is also the input of the front wheel system.

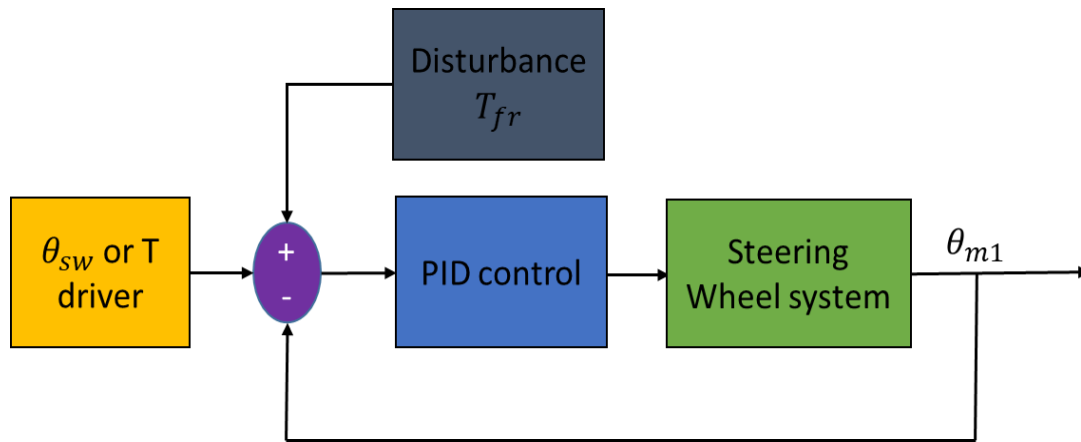


Figure 3.18: Steering Wheel system block diagram

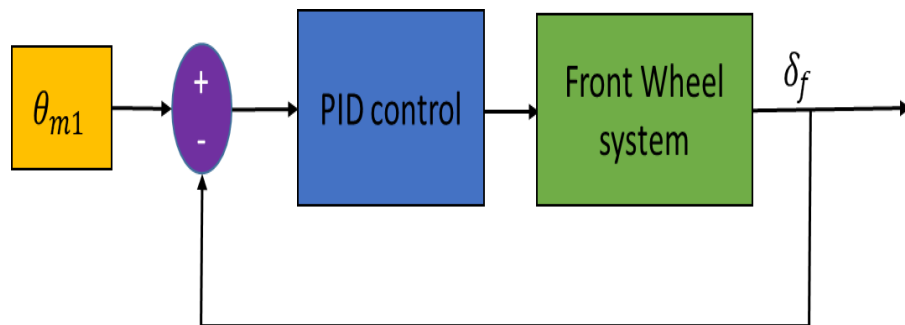


Figure 3.19: Front Wheel system block diagram

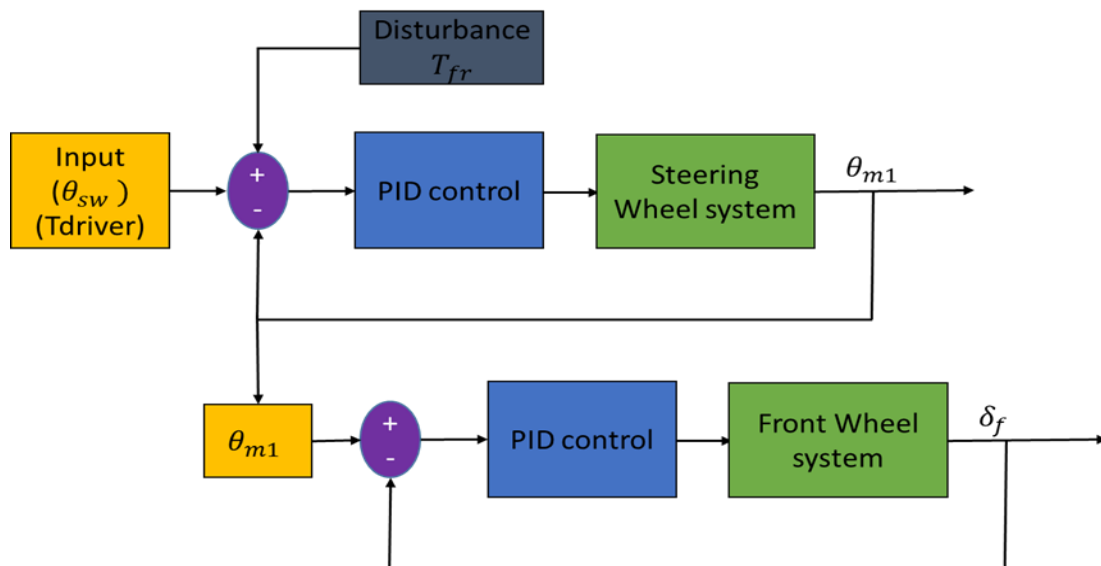


Figure 3.20: Block diagram of Vehicle SBW system

Fig. 3.20 shows the block diagram for the control structure of the steer by wire system (SBW). It includes the steering wheel system, the front wheel system and the controller. Two PID controllers were used for steering wheel and front wheel system. When the driver holds and turn the steering wheel, an adjustable angle is created by the motor of the steering wheel system, the PID controller will adjust the steering angle to a desired angle by calculating error. This angle will substitute in to the front wheel system and feedback to the PID controller.

A direction controller is used to control the vehicle in the left and right directions. A PID controller is used to design a left and right-turning controller for the 2021 Hyundai Ioniq Electric vehicle in this research.

To control the tire angle for the vehicle the parameters of the PID controller are tuned by using grey wolf optimization (GWO) and genetic algorithm (GA). Tuning the parameters of controllers using these two methods helps to compare which tuning algorithm is best for this specified application. This algorithm is compared in terms of rise time, settling time and overshoot.

The GWO and GA are employed for adjusting of the control parameters with respect to the proposed cost function (J). The tuning ranges of the parameters are set as denoted in Table 3.5, the parameters of the proposed algorithms are given.

Table 3.5: The parameters of the proposed algorithms

Algorithm	Parameters of algorithm	
GWO	Number of Search Agent	30
	Maximum Iteration	30
GA	Population size	30
	Generation	30

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

To investigate the effectiveness of the proposed control algorithm, a computer simulation based on MATLAB/Simulink software were conducted and output responses are compared with passive system.

Open loop for steering wheel system with and without disturbance

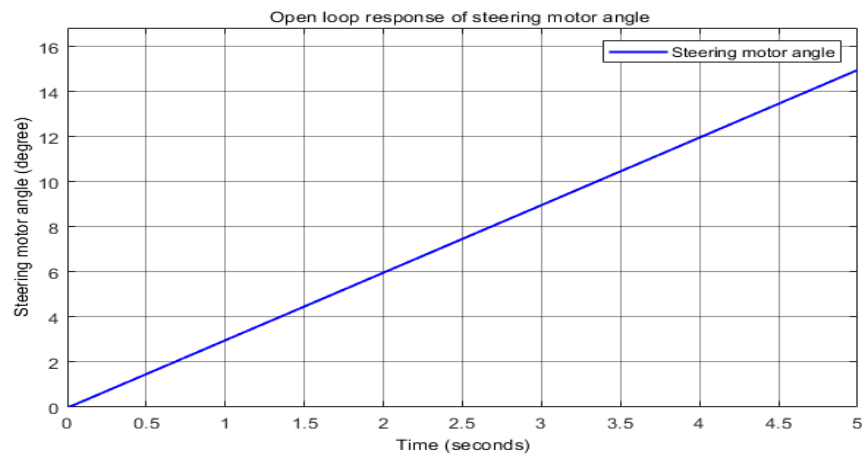


Figure 4.1: Open loop for steering wheel system without disturbance

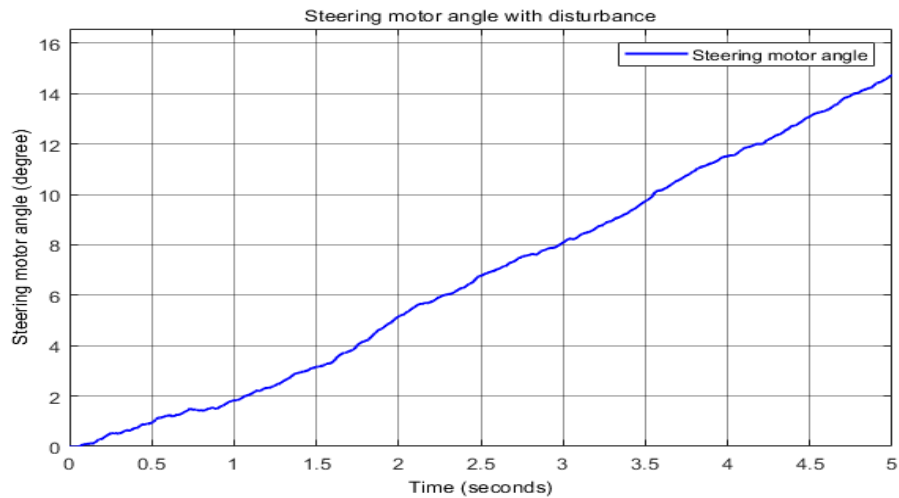


Figure 4.2: Open loop for steering wheel system with disturbance

Based on Fig. 4.1 and Fig 4.2, the steering motor angle (θ_m) response is unstable without disturbance in open loop system (without using controller) and with disturbance steering wheel system response is highly nonlinear system and unstable. The steering motor output is rapidly increase for small input signal thus it needs a controller like PID. The steer by wire design is created by combining the steering wheel subsystem and front wheel subsystem controlled by PID controller.

4.2 Simulation setup

4.2.1 Steering wheel system

In the simulation two scenarios were conducted for steering wheel subsystem case 1 without disturbance input and case 2 with a disturbance inputs.

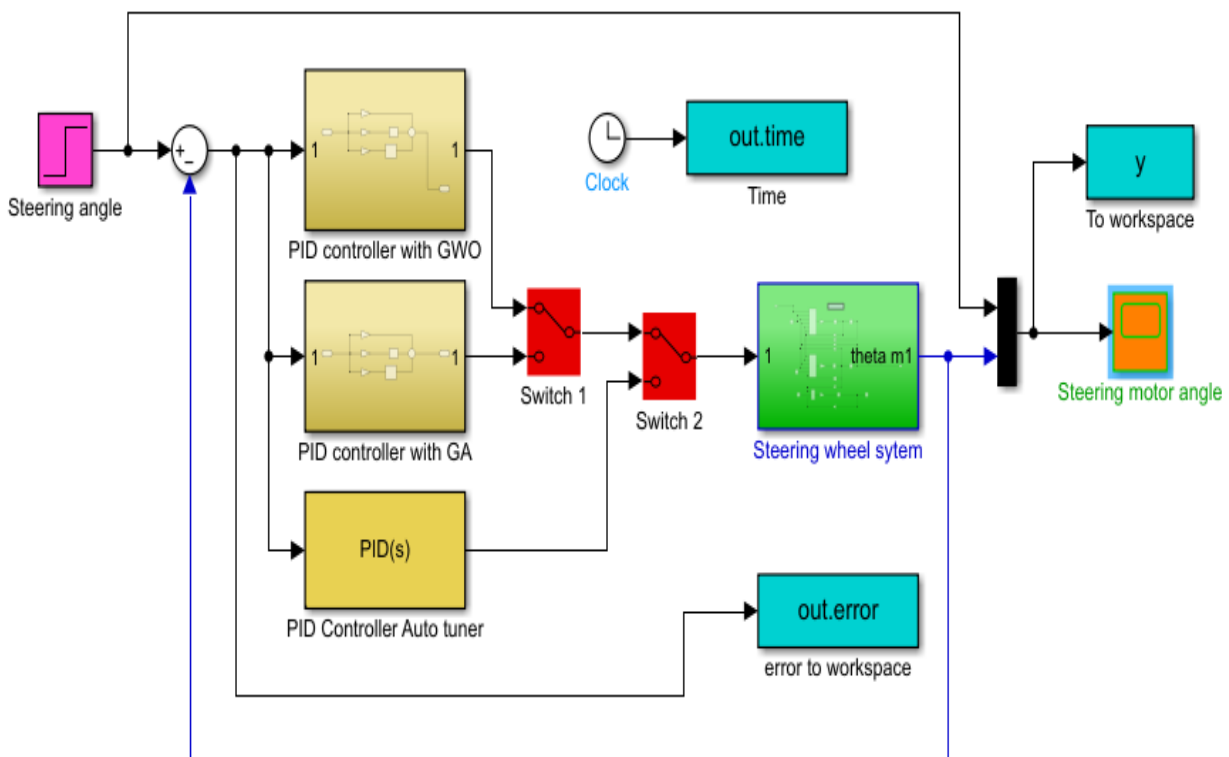


Figure 4.3: Steering wheel system Simulink block

The input to the system is a steering angle or driver torque simulated as a step response. The torque friction (T_{fr}) and the torque motor (T_m), react as disturbance input, in the steering where torque friction (T_{fr}) is created using random noise.

Some discription of the MATLAB/Simulink model in Figure 4.3.

1. The yellow color shows the designed controller used in this work (i.e., PID with GWO and GA algorithm and PID with auto tuner on Simulink).
2. The red color shows the manual switch of the system. Both switch 1 and switch 2 is used for interchanging a PID controllers with the plant (steering wheel system). In the above Figure switch 1 connects a PID controller with GWO algorithm and steering wheel system. GWO code is written on MATLAB script have direct relation with Simulink model and by varying number population, number of generation, upper bound and lower bound we get best Kp, Ki and Kd values by running the program.
3. The Green color shows the plant (steering wheel system).
4. The magenta color shows the reference angle direction control (steering motor angle).
5. The orange color shows the response of output path reference angle and steering motor angular displacement.
6. The cyan color shows the error, time and out files sent to work space.
7. The light green color or steering wheel system Simulink model was developed by SBW mathematical equations which is written in Chapter 3 and its Simulink model is in the appendixes.

Optimization by GWO and GA algorithm

Chapter 3 dealt with the design of the proposed controller and its optimal tuning of the three parameters Kp, Ki and Kd. Tuning the parameters was implemented by GWO and GA algorithm separately on MATLAB 2021a, using the following parameters.

For both GWO algorithm and GA algorithm maximum number of population and generation is similar 30 but their lower and upper bound is different for GWO Lower bound (LB): [0 0 0] and Upper bound (UB): [170 700 3]; for GA algorithm LB [0 0 0] and UP [150 1300 3] respectively.

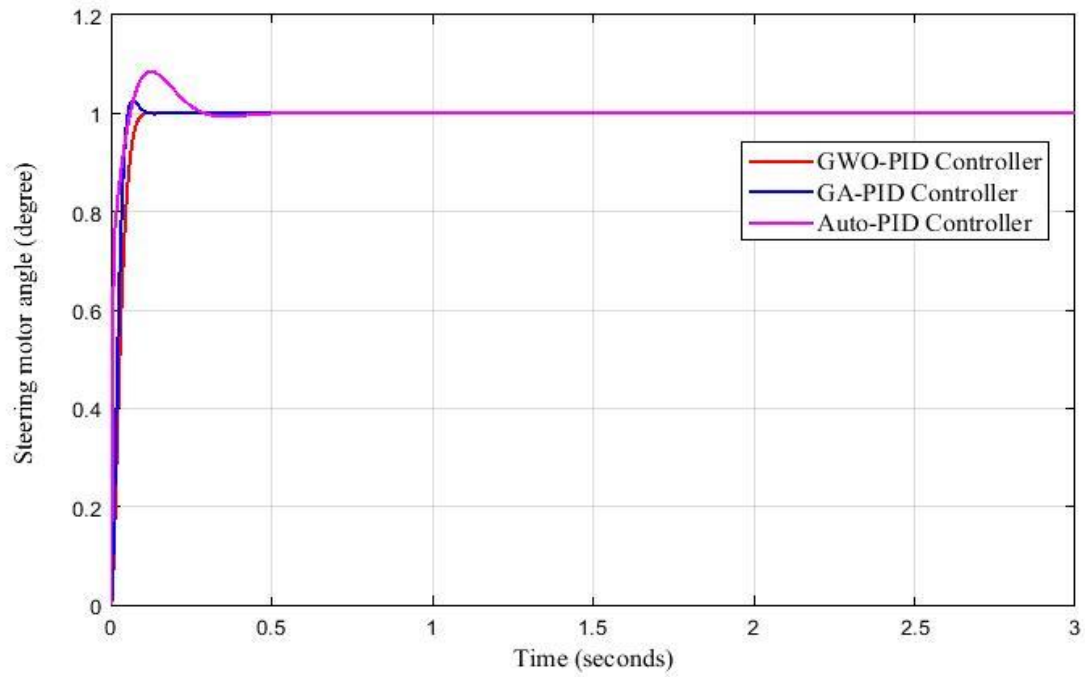


Figure 4. 4: Comparison of result obtained by GWO, GA and Auto tune based on PID controller for steering wheel system

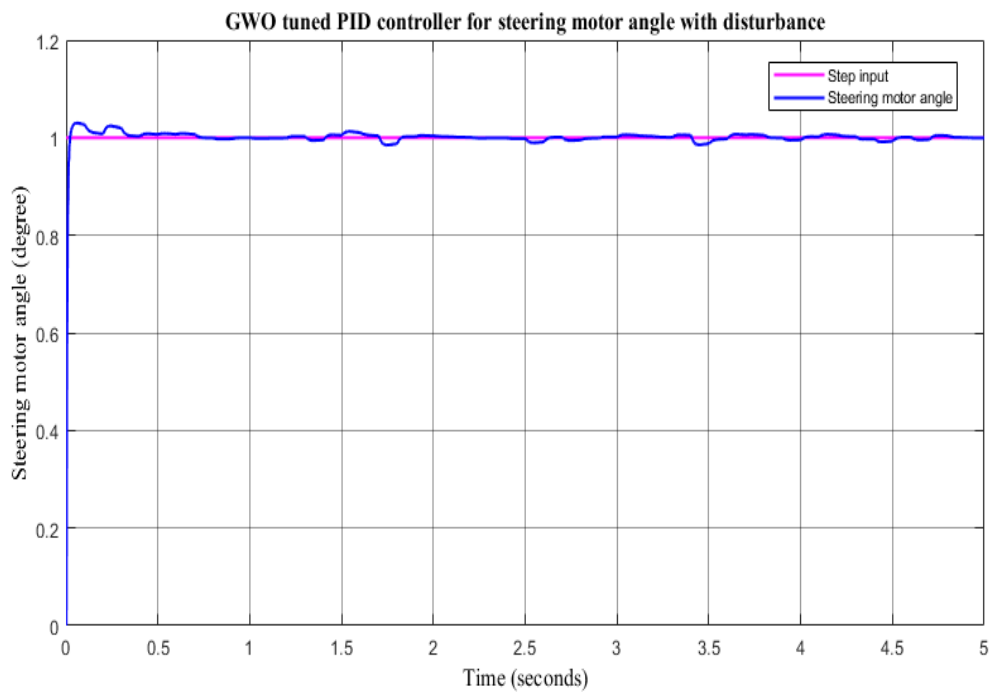


Figure 4.5: GWO tuned PID controller with disturbance

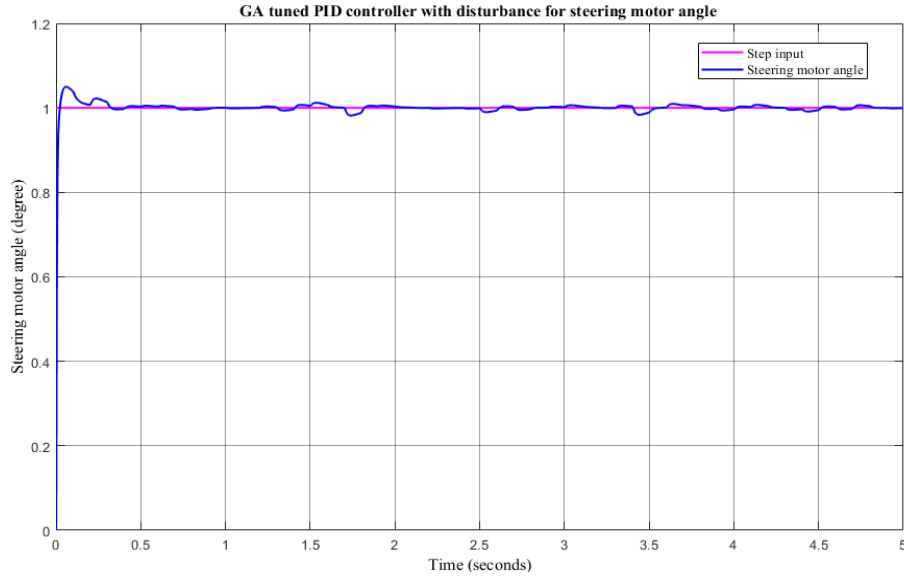


Figure 4.6: GA tuned PID controller with disturbance

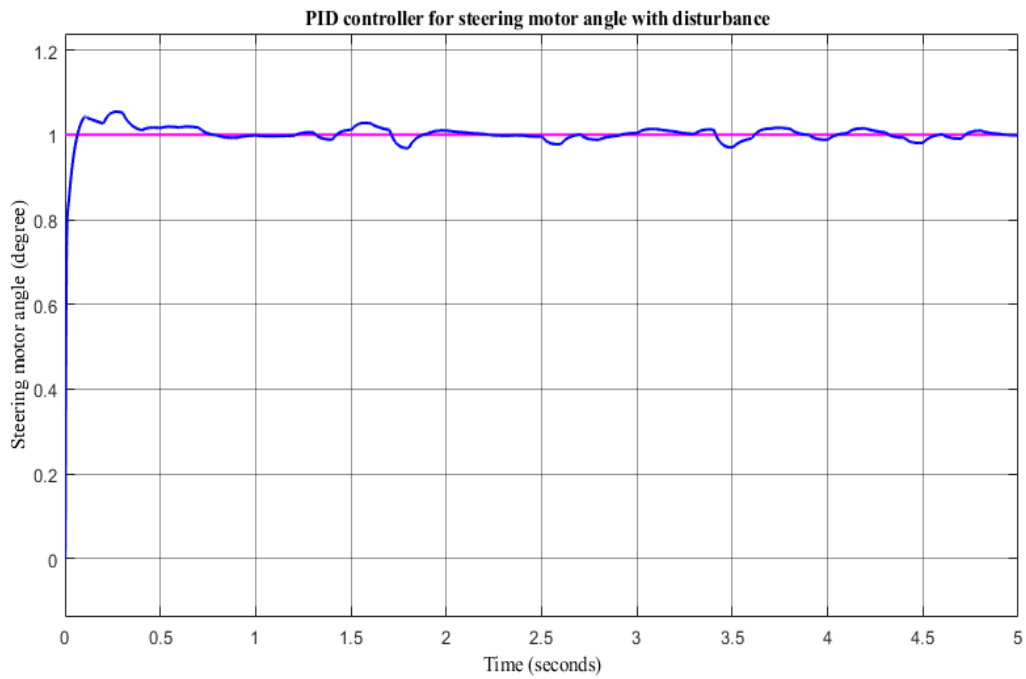


Figure 4.7: PID controller optimized by MATLAB auto with disturbance

The above shown Figures (Fig. 4.4 – Fig 4.7) shows that GWO, GA and MATLAB/Simulink auto tuned PID controller based steering wheel system with disturbance and without disturbance. The PID parametric values (K_p , K_i and K_d) from the above Simulink are written in the below Table.

Table 4.1: PID tuned controller parameters of steering wheel system without disturbance

Parameter	Without Disturbance			
	Parameter names	PID controller	GA PID controller	GWO PID controller
Kp	Proportion gain	60	49.8546	35
Ki	Integral gain	800	46.2148	33
Kd	Derivative gain	1.756	0.0661	0.06

Table 4.2: PID tuned controller parameters of steering wheel system with disturbance

Parameter	With Disturbance		
	PID controller	GA PID controller	GWO PID controller
Kp	70	150.254	165.242
Ki	300	1299.715	696.383
Kd	1.756	1.682	1.620

Table 4.3: The Step info of tuned PID controller parameters of steering wheel system with disturbance

Algorithm	Steering angle (degree) at step input		
	Overshoot	Rise time	Settling time
GWO	3.0525	0.0099	0.3003
GA	5.0717	0.010	0.9080
MATLAB Auto tuner	5.5729	0.0291	3.5258

Table 4.4: The Step info of tuned PID controller parameters of steering wheel system without disturbance

Algorithm	Steering angle (degree) at step input		
	Overshoot	Rise time	Settling time
GWO	0.1352	0.0494	0.0800
GA	2.5770	0.0327	0.0808
MATLAB Auto tuner	8.4762	0.0330	0.2391

The values from Table 4.1 to Table 4.4 are obtained from the optimization algorithm which written in Appendix. In this algorithm the lower bound, upper bound, population size and maximum generations are written in MATLAB script with the program and the Simulink model is drawn in MATLAB Simulink so, when the optimization code is run it calculates the best PID parameter values. GWO algorithm is more recent and updated than GA algorithm (Mirjalili et al. 2014). It solves many problems with best results in other literature also in this study it gives fast response.

The parameters of the controller (PID) are tuned (optimized) using three optimization algorithms (GWO, GA and MATLAB Auto tuner). The comparison of GWO, GA and MATLAB Auto tuner algorithms for PID controller are shown from Figure 4.4 to Figure 4.7. With a step input steering angle for steering wheel system. For the system to be stable maximum peak overshoot should be less and the settling time must be less so that the stability of response is increased. The simulation result shows that in a given time domain specification and GWO has a small overshoot, no undershoot, and lower settling time than others. Even with high disturbance inputs which affect the control-system's output, and result in an increase of the system error. The PID tuned parameters can partially eliminate the effects of disturbances on the output and system error. So they improved the stability of the system, reduces the steady-state error, reduces vibration and makes the system faster by reducing the time constant.

GWO has better response than GA and MATLAB Auto tuner optimization algorithms in terms of time domain specification, as shown in Figure 4.4. This result shows that a GWO based PID is good at in steering motor angle response.

4.2.2 Front Wheel System

In front wheel system, steering motor angle is the input to the system which is the output of steering wheel system and tire angle the final output.

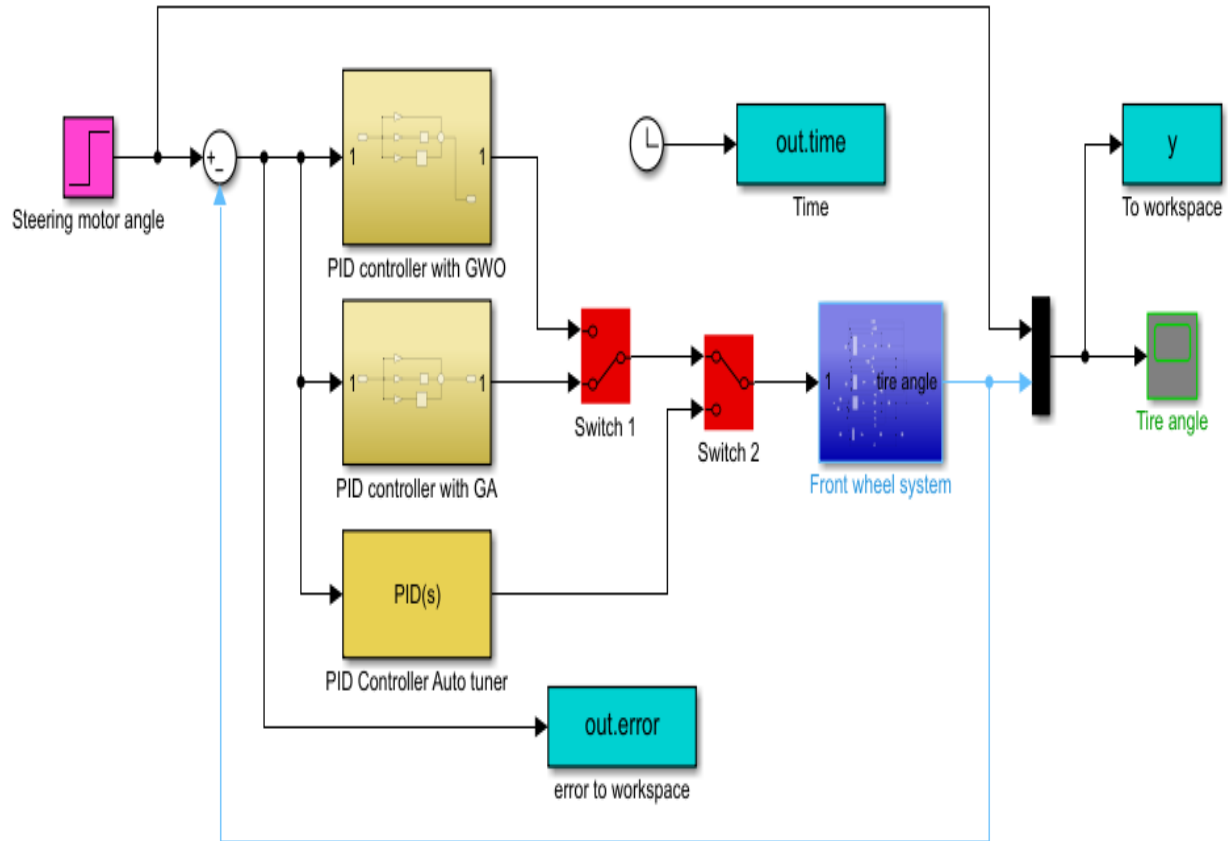


Figure 4.8: Front wheel system Simulink block

Some discription of the MATLAB/Simulink model in Figure 4.8.

1. The yellow color shows the designed controller used in this work (i.e., PID).
2. The red color shows the manual switch of the system. In the above Figure switch 1 connects a PID controller with GA algorithm and Front wheel system. GA code is written on MATLAB script have direct relation with Simulink model and by varying number population, number of generation, upper bound and lower bound. The best K_p , K_i and K_d values obtained by tri and error many times.
3. The light blue color shows the plant (Front wheel system).

4. The magenta color shows the reference angle direction control (steering motor angle with front tire angle).
5. The green color shows the response of output path reference angle and front tire angle.
6. The cyan color shows the error, time and out files sent to work space.
7. The front wheel system in blue color which is developed from the mathematical equations of SBW which was dealt in chapter 3; its Simulink model is in the appendixes.

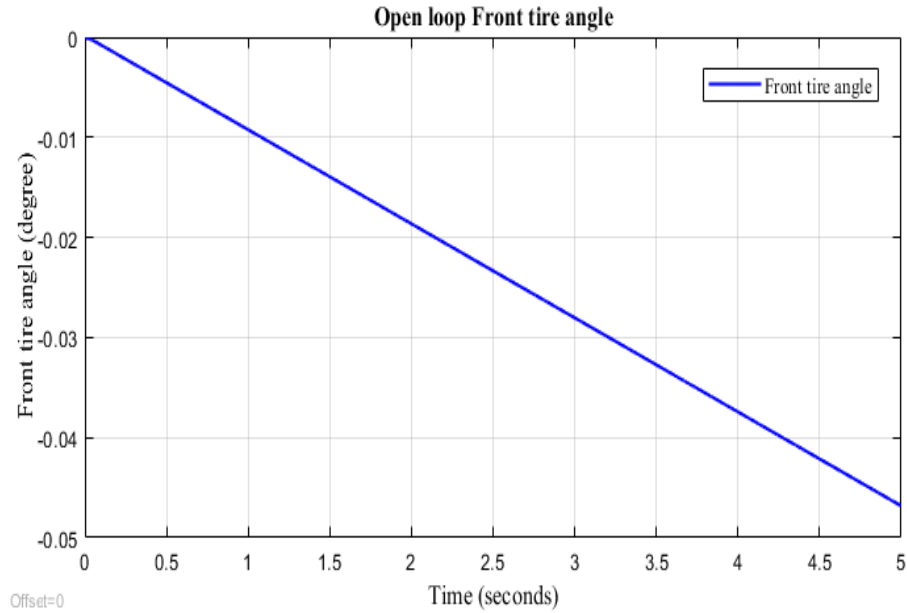


Figure 4.9: Open loop front tire angle

The Lower Bound (LU) and Upper Bound (UP) of GWO and GA algorithm are given for GWO LB [0 0 0] and UB [900 40 3] and for GA algorithm LB [0 0 0] and UB [1200 70 3] respectively.

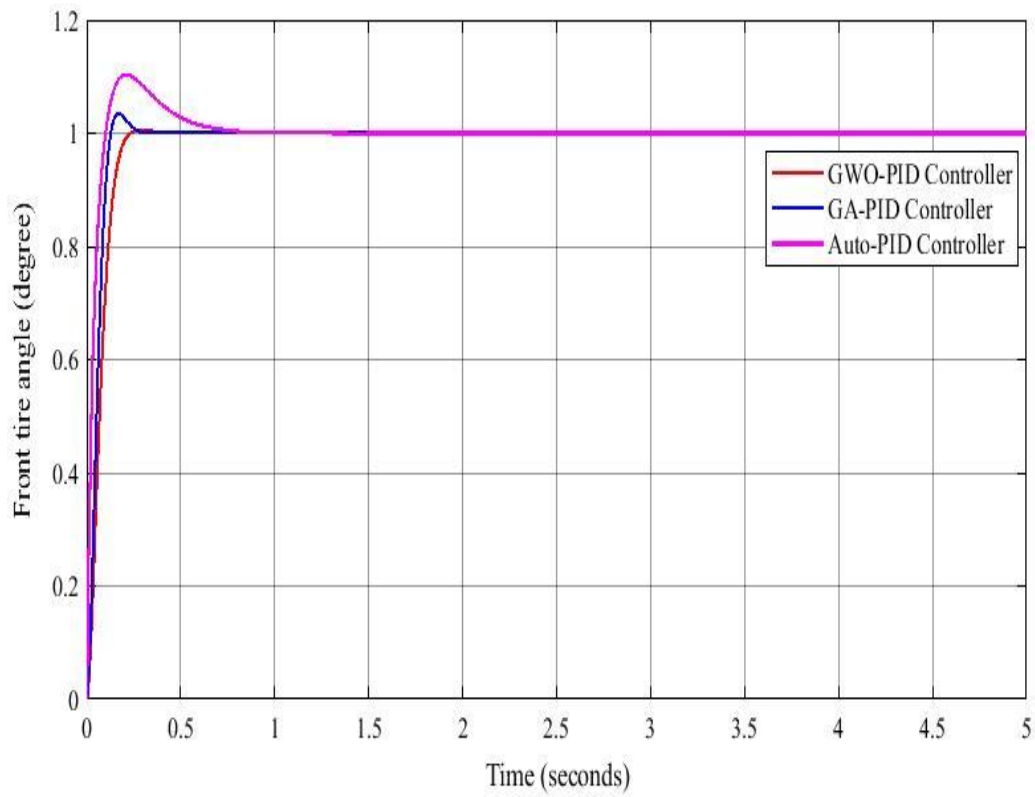


Figure 4.10: Comparison results obtained by GWO, GA and Auto tune based PID controller for front wheel system

The above shown Fig 4.10 shows that a PID controller optimized by three algorithms and its best PID gain values and its step response information (rise time, settling time and overshoot) is written in following tables.

Table 4.5: PID tuned controller parameters of front wheel system

Parameter gain	Tire angle (degree) at step input		
	PID controller	GA PID controller	GWO PID controller
Kp	1734.751	1289.874	900
Ki	7145.920	65	40
Kd	49.097	1.031	1.0237

Table 4.6: The Step info of tuned PID controller parameters of front wheel system

Algorithm	Tire angle (degree) at step input		
	Overshoot	Rise time	Settling time
GWO	0.3511	0.1216	0.1940
GA	3.3733	0.0818	0.2139
MATLAB Auto tuner	10.2157	0.0654	0.5519

4.2.3 Over all structure of SBW system

In this case we simulate both steering wheel system and front wheel system together; the steering wheel system is used as a reference or step input to the front system diagram and vehicle tire angle is the final desired output. The Figure 4.11 shows that steer by wire system PID controller tuned GWO, GA and MATLAB/Simulink response for steering wheel angle and front wheel angle. The results show that steering wheel angle can track the desired T_{driver} with lower settling time and lower overshoot.

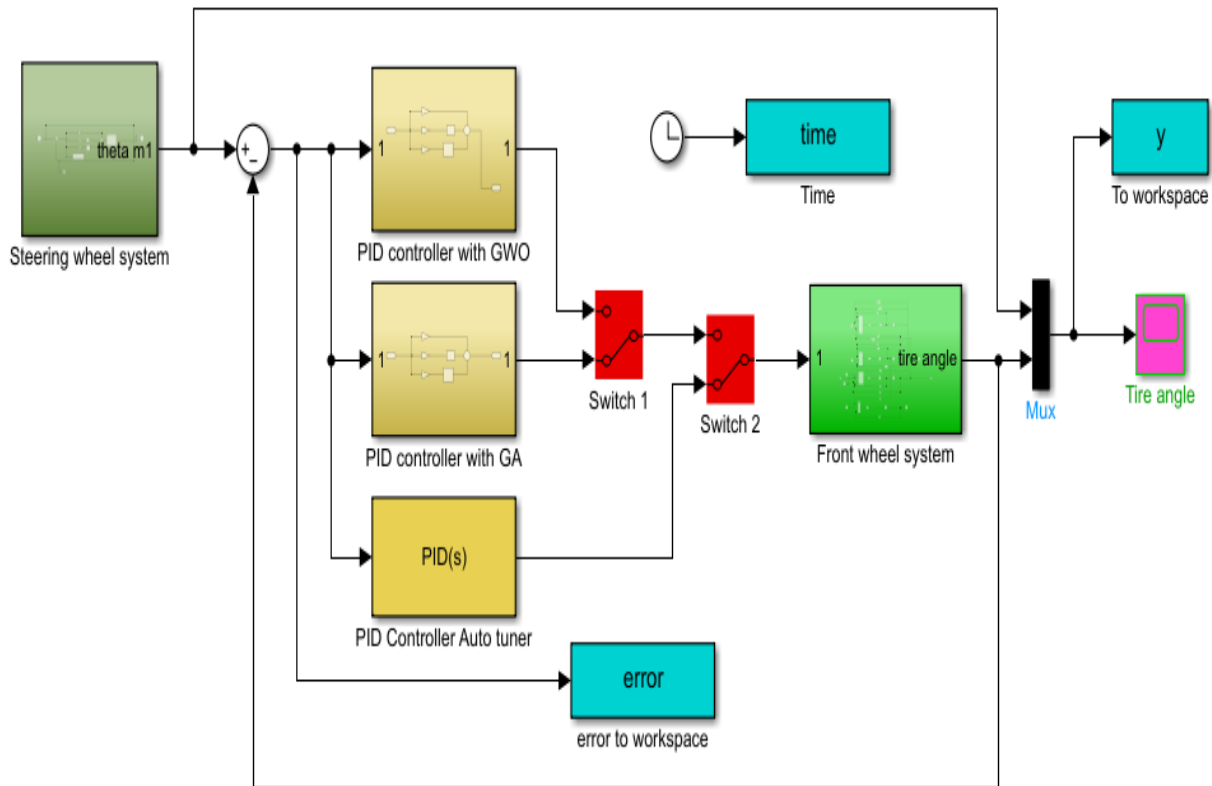


Figure 4.11: MATLAB/Simulink model of Steer by wire (SBW)

Some description of the MATLAB/SIMULINK model in Figure 4.11.

1. The orange color shows the designed controllers used in this work (PID tuned with GWO, GA and MATLAB/Simulink Auto tuner).
2. The red color shows the manual switch of the system. When switch 2 is in connected with PID controller we get tire angle response optimized by MATLAB/Simulink auto tuner.
3. The dark green shows that the reference input to the Front wheel system which is steering wheel system output (steering angle). Steering wheel system Simulink designed in Figure 4.3. is created to subsystem which is used as input to the system in overall SBW structure.
4. The green show the plant which required to control (front wheel system or front tire angle).
5. The canvas color shows the time, error and output file to MATLAB work space.

From the result, it clearly shows that both angles can track the desired input with minimal error about. In this findings a PID controller can improve the performance of the vehicle steer by wire system in terms of input directional control and wheel synchronization.

For GWO algorithm the Lower bound (LB): [0 0 0] and Upper bound (UB): [2300 40 35] and for GA algorithm Lower bound (LB): [0 0 0] and Upper bound (UB): [1200 700 1] are given respectively for simulation purpose.

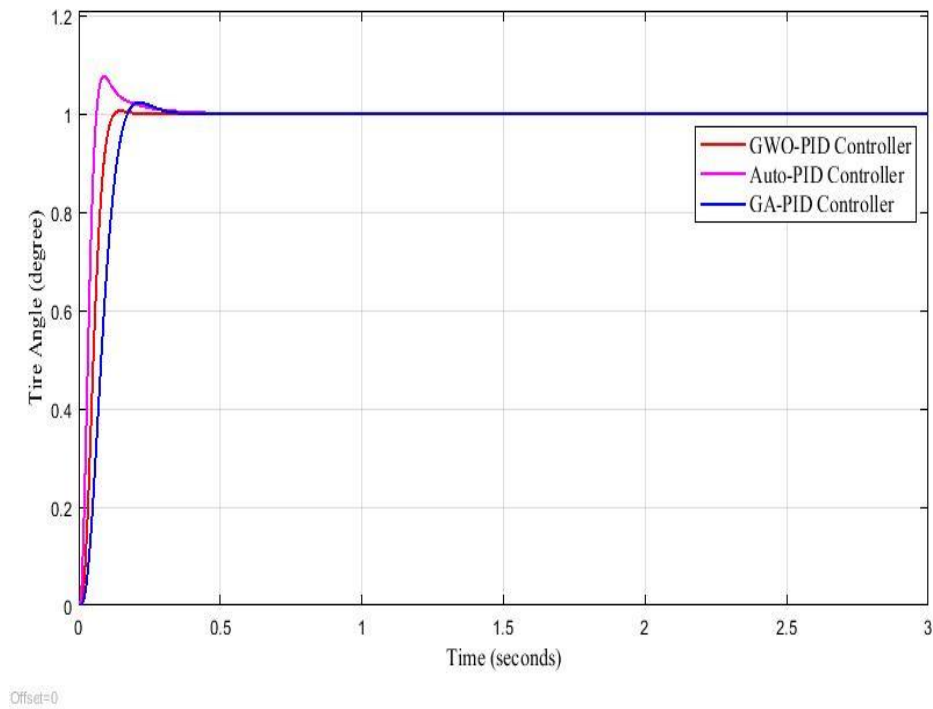


Figure 4.12: Comparison of result obtained by GWO, GA and Auto tune based PID controller for overall steer by wire system

Table 4.7: PID tuned controller parameters of vehicle SBW system

Parameter	Tire angle (degree) at step input		
	PID controller	GA PID controller	GWO PID controller
Kp	7386.144	1200	2300
Ki	56188.299	65	31
Kd	98.424	1	31

Table 4.8: The Step info of tuned PID controller parameters of vehicle SBW system

Algorithms	Tire angle (degree) at step input		
	Overshoot	Rise time	Settling time
GWO	0.6032	0.0640	0.1105
GA	2.1263	0.0980	0.2293
MATLAB Auto tuner	7.5229	0.0485	0.1983

The simulation results show that the proposed vehicle steer by wire (VSBW) optimized by GWO algorithm produces 0.6032% overshoot means its operation is smooth and no vibration when it reaches its desired tire angle positions and has a settling time of 0.1105s and a rise time of 0.0640s, which is lower than others. The GA and Matlab auto tuner have 2.1263% and 7.5229% overshoot, 0.0980s and 0.0485s rise time, 0.2293s and 0.1983 settling time, respectively.

This shows that the PID controller designed using GWO can effectively and efficiently control the operation of steering angle motor and tire angle while ensuring the comfort of passengers and ensuring a smooth driving system. With a step input steering motor angle for front wheel steering system. GWO has better performance response than GA and MATLAB Auto tuner optimization algorithms in terms of time domain specification, as shown in Table 4.8 below. This result shows that a GWO based PID is good at in steering motor angle response because it gives a faster and more accurate response and the error of the controller is reduced too. The results obtained of vehicle motion can be maintained in accordance with the desired steering angle input with smaller error and was able to achieve disturbance than with the control system using other tuning algorithms.

4.3 Validation of the results with other published paper results

(Fahami et al., 2012) In this paper, control strategy and mathematical modelling for a steer by wire system (SBW) was presented. From the simulation, it can be analyzed that by using the PID controller, the front tire angle (δ_f) is stable even disturbance and torque are applied. Based on the results, the controller is able to reduce the disturbance error. They used MATLAB/SIMULINK

auto tuner PID to optimize the results. The results they got from the simulation environment is shown in the Figure below.

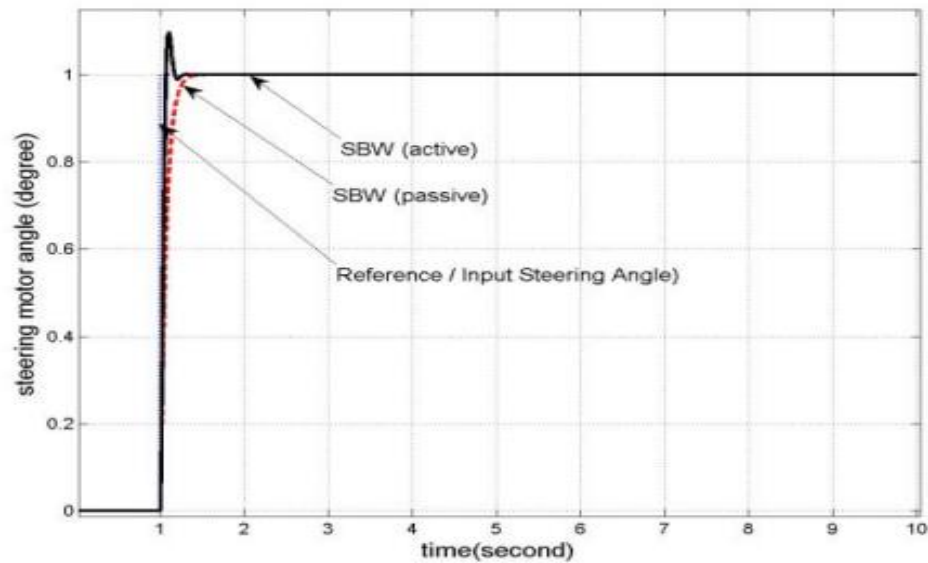


Figure 4.13: Steering motor angular displacement (without disturbance)

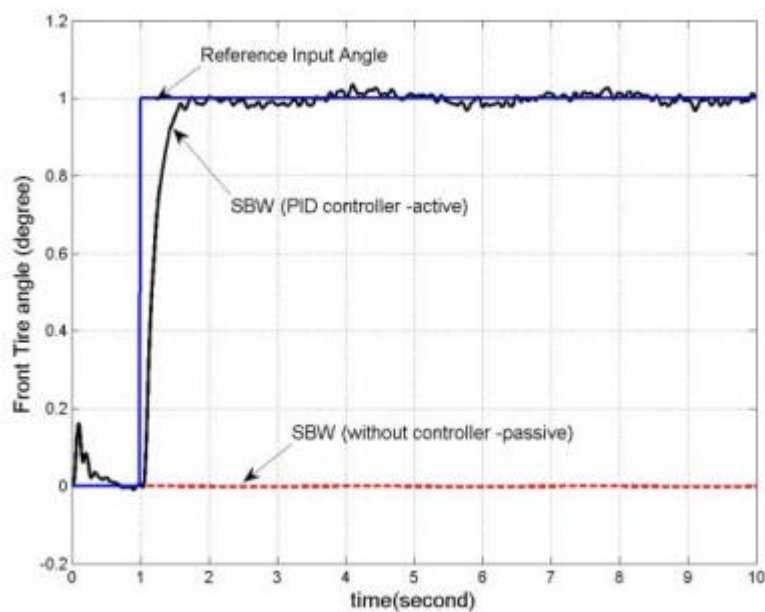


Figure 4.14: Front Tire angle (with disturbance)

The above Figure 13 and Figure 14 shows that the they used sample time 1s in step input (reference input) and 10s for simulation time. They didn't calculate rise time, settling time and over shoot but

the results they got looks similar with my work. The results from GA and GWO algorithm in Figure 4.12 shows the better results.

(Zaidi et al., 2017) they used tradition method (Ziegler Nichols method) for tuning the PID parameters. Figure 6 shows the step response for steering wheel steering motor angle and front wheel tire angle. Their results show that steering wheel angle can track the desired Torque of driver with zero steady state error and percentage overshoot, %OS = 10%.

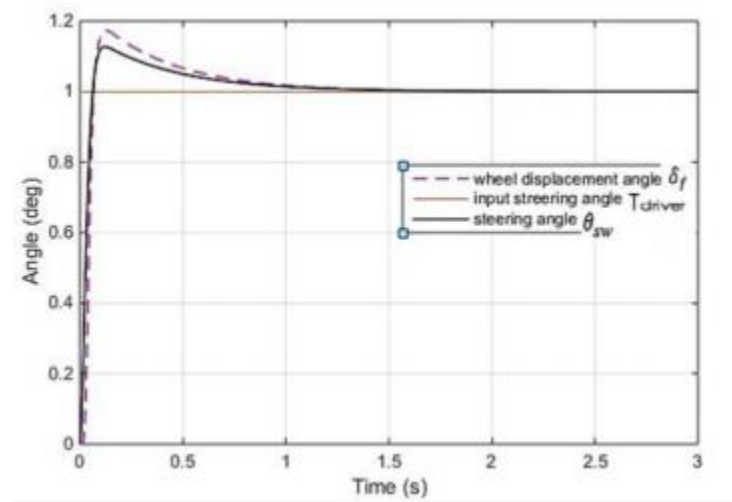


Figure 4.15: Step response for θ_{sw} and δ_f

When we compare (Zaidi et al., 2017) and (Fahami et al., 2012) results Fahami steering performance is better than Zaidi because it used PID auto tuner optimization algorithm which gives good result than traditional method. In addition, by using GWO and GA tuning mechanism we can get fast and accurate vehicle steer by wire (SBW) responses. When we reduce the controller error by tuning PID by GWO algorithm the effective and efficient tire angle is respond.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this paper, mathematical model and control strategy for a steer by wire system was proposed. A SBW is a highly nonlinear and unstable system without any controller, the response of the plant is not stable (very rapid increase in output due to small input signal) as shown in the result of open loop response.

Vehicle parameters like mass of car, steering wheel components, front wheel components and BLDC motor parameters are identified for mathematical design of the SBW in MATLAB/Simulink. The controller used in this work (PID) parameters are tuned using grey wolf optimization (GWO), genetic algorithm (GA) and MATLAB auto optimization. These optimization algorithms are compared in terms of overshoot, settling time and rise time, and their results show that GWO has a smaller overshoot and lower settling time when compared with GA and MATLAB auto tuner in time response specifications with and without disturbances.

Based on the results, the controller is able to reduce the disturbance error. So, it can be concluded that by using the PID controller, the front tire angle (δ_f) is stable even disturbance and torque are applied. The PID controller tuned using GWO are good at directional control of the vehicle when compared with GA and MATLAB auto optimization as shown in the simulation results.

Thus the proposed control strategy has smooth operation by avoiding the vibration that occurs by the overshoot using GWO-PID controller. The system performance checked with disturbance and without disturbance at different Torque driver input and steering angle.

5.2 Recommendations

Nowadays, transportation is a fast-growing industry. The drive by wire system is one of the future technology widely used. This work is limited to simulation using MATLAB/Simulink. It is recommended the hardware implementation of this steer by wire design using PID in a real-time operating systems. On the other hand, on vehicle steer by wire system (VSBW), by adding some

future, it is possible to change it to an autonomous vehicle, lane detection and cruise control is used by all people and especially for those difficult to see.

5.3 Future works

To this end, there are still several future works to be carried out. They are listed as follows.

1. Improvement of experimental setup

It is under consideration to implement an SBW system to a real ground vehicle such that the dynamics of the SBW systems can be thoroughly reflected in experiments, and more effective control schemes can be experimentally implemented to the SBW equipped vehicles.

2. Vehicle Stability Control for SBW equipped vehicles

For future work, a yaw rate and body slip angle will be investigating to include into the system for in order to improvement the maneuverability and stability.

3. Vehicle brake-by-wire systems control design

Brake-by-Wire (BBW) technology is also an important part of the Drive-by Wire technology in automobile industry. The BBW system utilizes electromechanical actuators and communication networks to replace conventional mechanical or hydraulic devices such that enhanced safety and comfort can be achieved, cost related to manufacturing and maintenance can be cut off, and environmental concerns caused by hydraulic systems can be eliminated.

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APPENDIXES

Appendixes 1: Simulink block of Steer by Wire

Steering wheel system Simulink

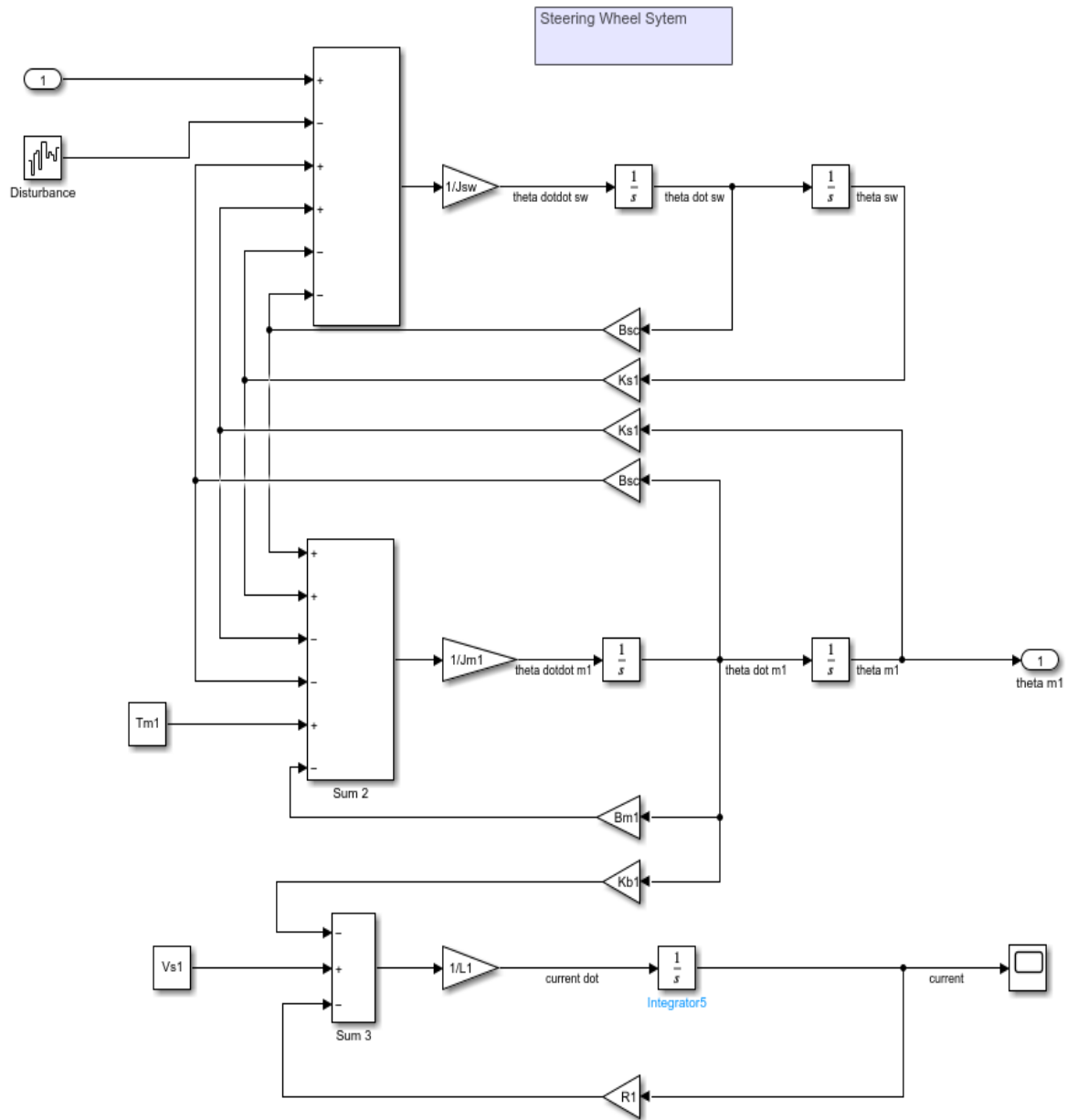


Fig. 1 Steering wheel block Simulink

Front wheel system Simulink

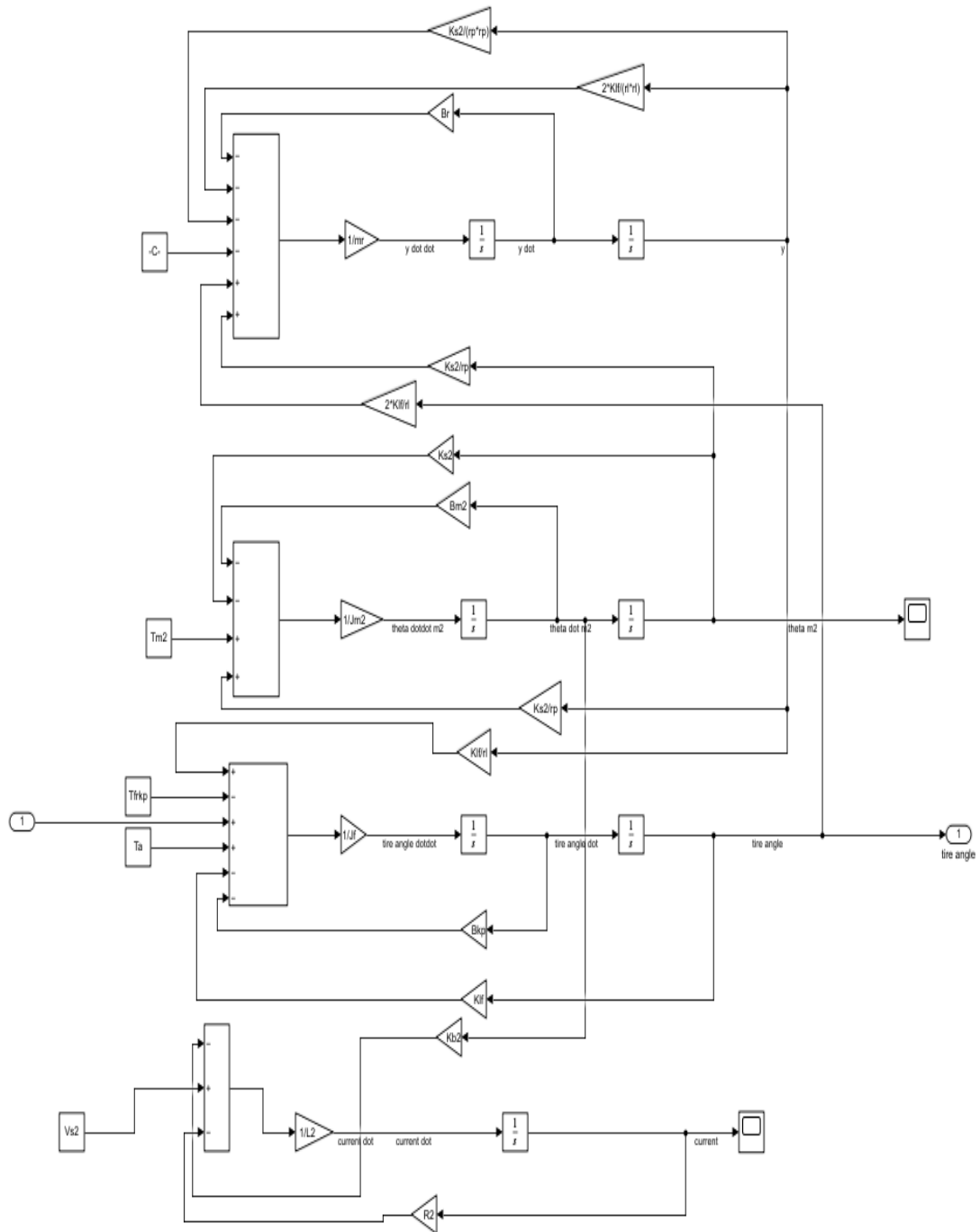


Fig 2: Front wheel system Simulink block

Steer wheel with disturbance GA Simulink

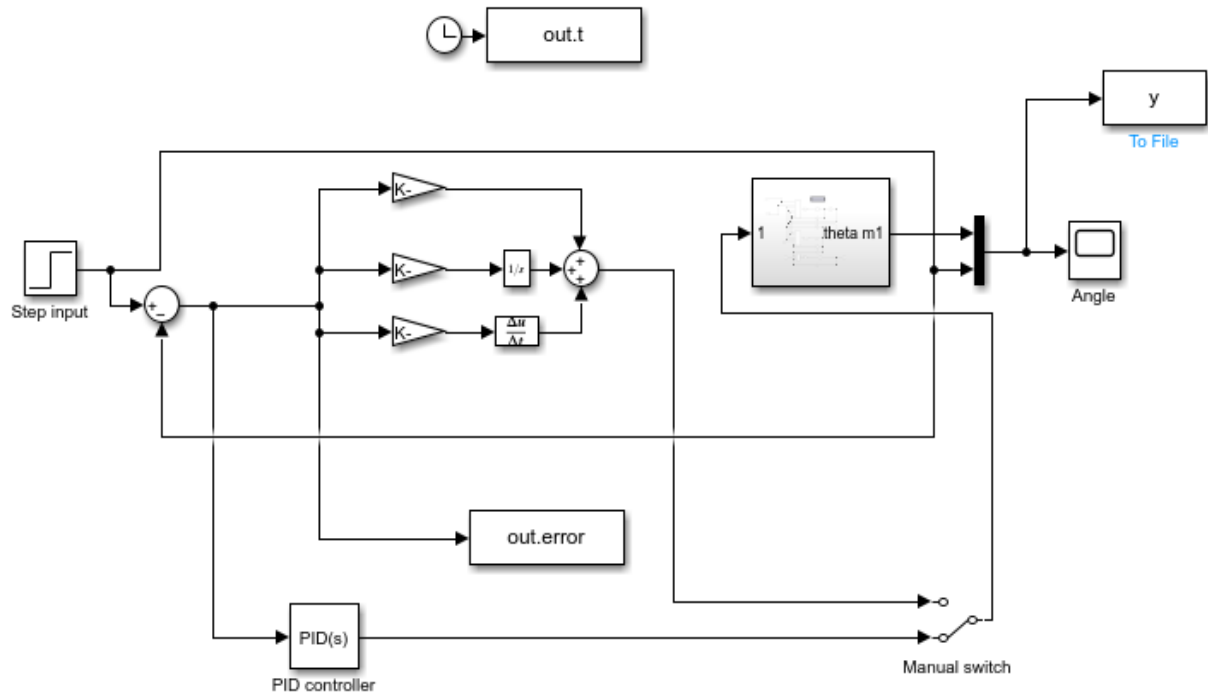


Fig 3. Steer wheel with disturbance GA Simulink block

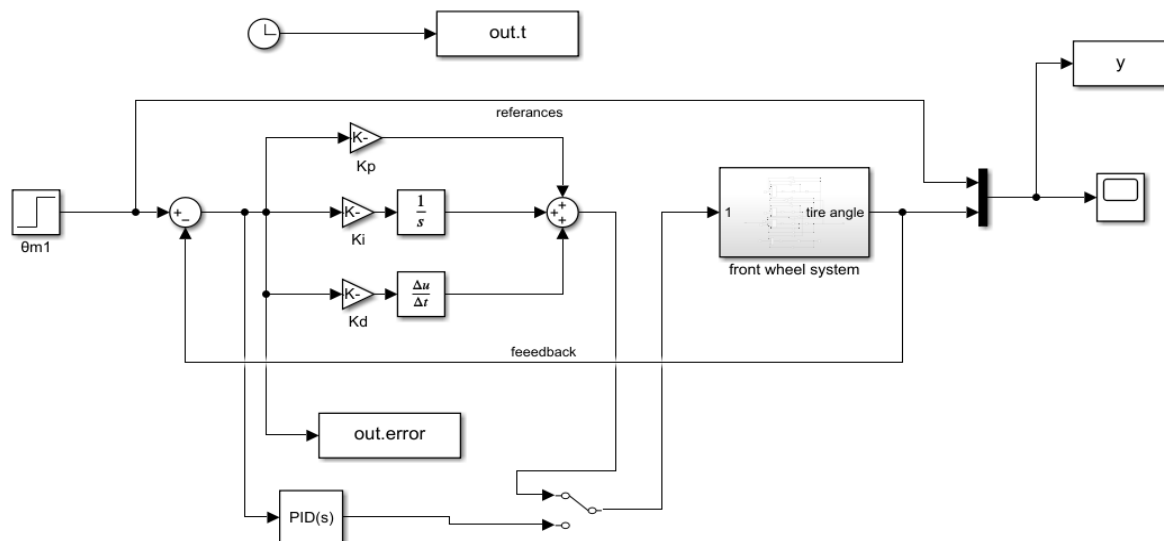


Fig 4. Front wheel GWO Simulink block

Steering wheel block Simulink Tuned by GWO and auto tuner

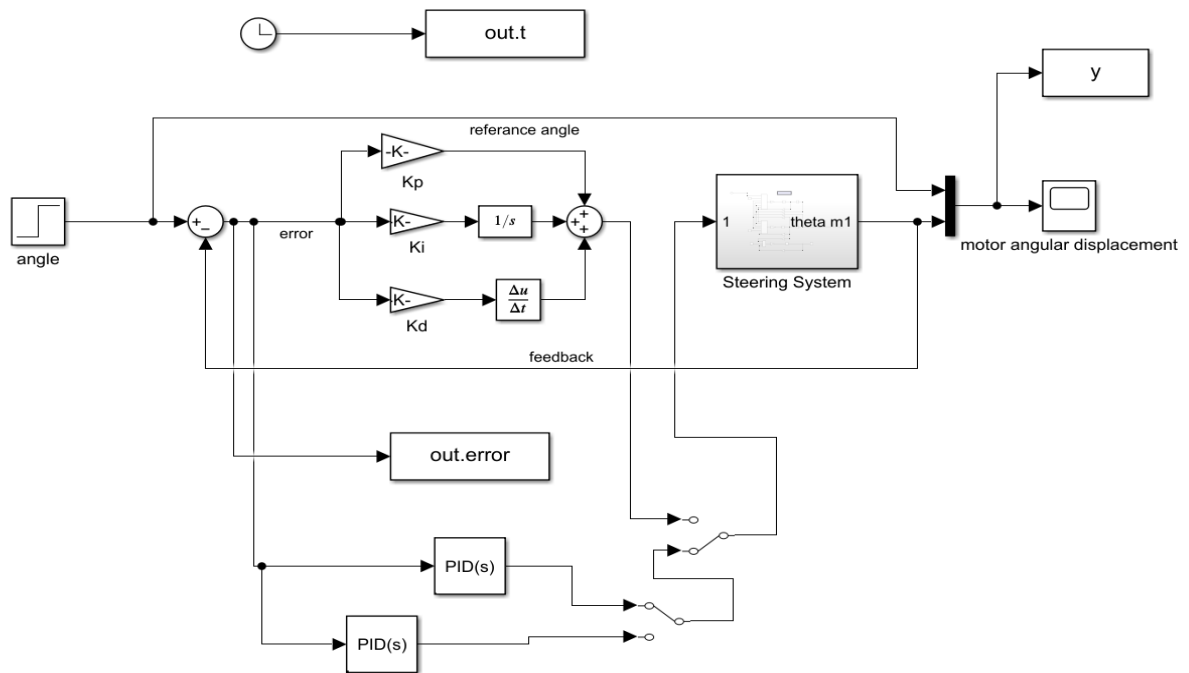


Fig. 5: Steering wheel block Simulink Tuned by GWO and auto tuner

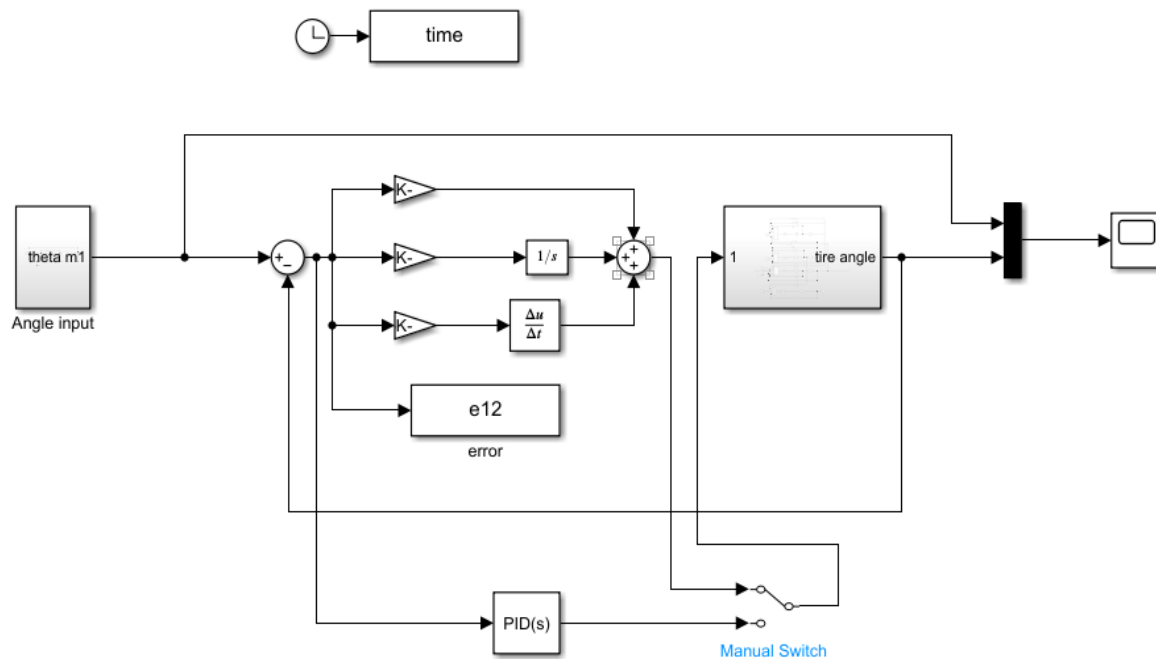


Fig. 6: Over all steer by wire Simulink model

Steer front Sim out

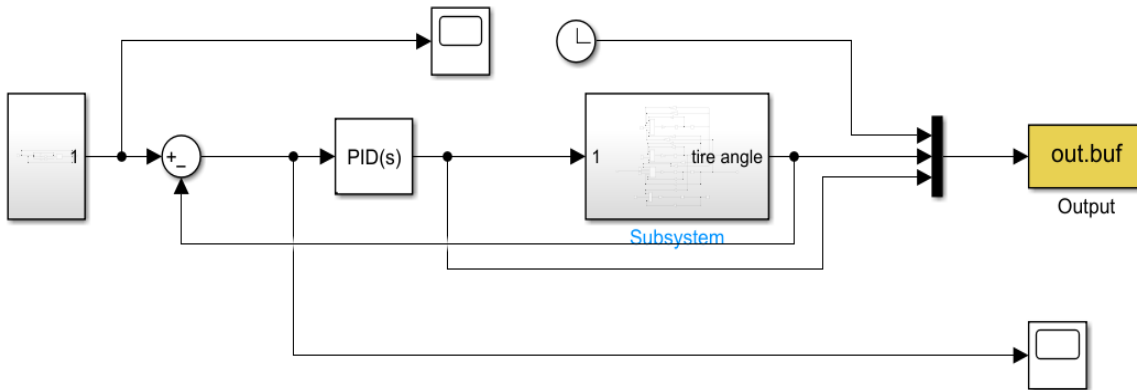


Fig. 7 Steer front simout

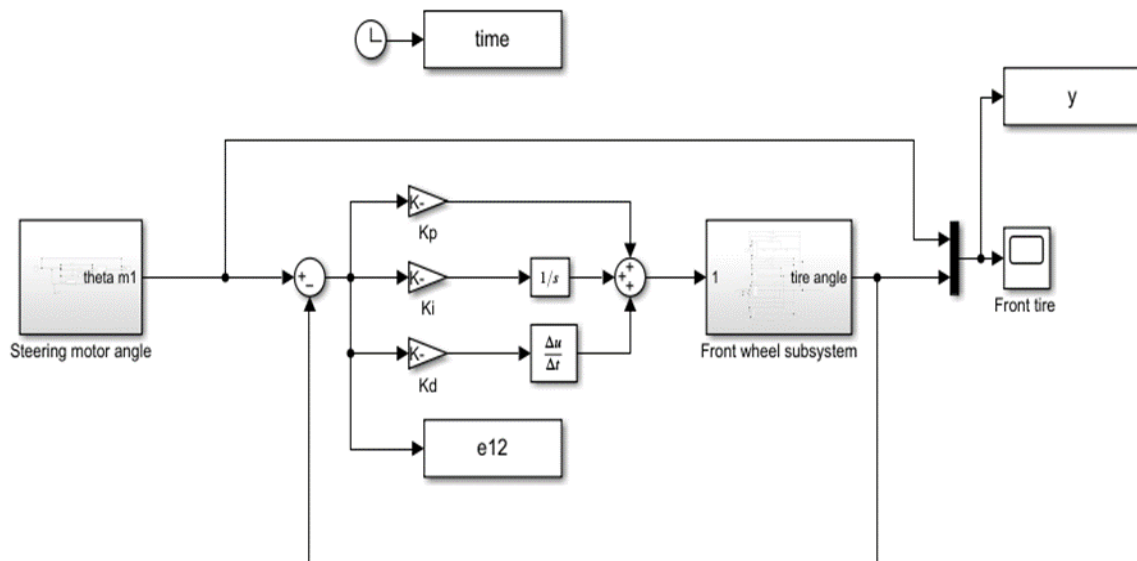


Fig. 8 Steer front GWO-PID controller

Appendix 2: Genetic optimization algorithm (GA code)

```
function steering_wheel_GA
clear;
clc;
close;
% rng default
options = optimoptions('ga','PlotFcn',@gaplotbestf);
options.PopulationSize = 30;
options.MaxGenerations = 30;
nvar = 3; % Number of parameters
LB = [0 0 0.01]; % Lower bound
UB = [60 60 0.07]; % Upper bound
[x,fval]=
ga(@EvalObj,nvar,[],[],[],[],LB,UB,[],options);
x'
%%
function obj = EvalObj(x)
simulink_model = 'steering_wheel';
load_system(simulink_model);
gains= get_param(simulink_model,'modelworkspace');
gains.assignin('Kp1', x(1));
gains.assignin('Ki1', x(2));
gains.assignin('Kd1', x(3));

simOut = sim(simulink_model,'SaveOutput','on');
t = simOut.find('t');
e1 = simOut.find('error');
%%
ea = t.*abs(e1); % ITAE
n=size(e1);
%%
obj= 0;
for i = 2:n
    stepsize = t(i)-t(i-1);
    obj = obj+0.5*(ea(i-1)+ea(i))*stepsize;
end
%%
```

Sim_PIDModel_SP

```
%% Simulate the tuned PID control system
% The simulink model needs three gains x= [Kp1 Ki1
Kd1].
x = [ 1000 40 1]; %fval = 3.2979
simulink_model= 'PIDModel2_SP';
load_system(simulink_model);
gains= get_param(simulink_model,'modelworkspace');
gains.assignin('Kp1', x(1));
gains.assignin('Ki1', x(2));
gains.assignin('Kd1', x(3));
% Simulates the simulink model to get the outputs
simOut= sim(simulink_model,'SaveOutput','on');
% Retrieves t and y
buf= simOut.find('buf');
t= buf(:,1);
y= buf(:,2);
u= buf(:,3);
subplot 211
plot(t,y,'linewidth',2)
axis([0 t(end) 0 1.2])
subplot 212
plot(t,u,'linewidth',2)
```

Appendix 3: Survey on Marathon Motors Engineering

Survey on Marathon Motors Engineering

1. Date: 17/02/2022

2. Name of Organization: Marathon Motors Engineering

3. When did Marathon Motor started assembling electric car?

Answer: Marathon Motors established in 2009. It is the leading importer of Hyundai brand cars in to Ethiopia. Collaboration with Hyundai Korea, the importer opened a car assembly plant in the country with an investment of half billion birr.

⊗ Marathon introduce the first fully locally assembled electric car in Jun 2020.

4. What type of steering system does electric car use?

Answer: Hyundai Ionic electric car use electric power assisted steering system.

5. From which country electric vehicle components are imported, especially steering system parts?

Answer: The Marathon Motor Engineering PLC is a joint Venture between South Korean automobile Manufacturer Hyundai Motor Company and Ethiopian former long distance runner Haile Gebrselassie. All components are imported from South Korea.

6. Which type of light car is mainly used in Ethiopian currently? Why?

Answer: Today in Ethiopia Toyota cars are widely used by government and by customers. But the Toyota cars used by customer society are mainly second hand vehicles. Because of their low cost and has many spare parts. So their steering system is fair easy because of they changed from Right to left hand wheel.

7. What is the next plan of Marathon Motor Engineering?

Answer: Marathon motor aspires to become Africa's largest car manufacturer through tariff protection and by increasing the number of assembling plants, coming up with Unique in Ethiopia engine car called Africar.