Design of CAN Based Electronic Differential System of an Electric Vehicle

A Thesis submitted to the Faculty of Engineering and Technology, Jadavpur University in partial fulfilment of the requirements for the degree of Master of Engineering in Power Engineering

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Abstract

Over the past few decades, the target research domain has shifted towards developing eco-friendly, energy efficient automotive system which would, in a way, serves both the economical and luxury benefits of mankind. One such confronting research domain is the field of Electric Vehicles (EVs) and an integral part of an EV is Electronic Differential (ED).This dissertation proposes an Electronic Differential (ED) system for a 4 wheel drive and 4 wheel steering (4WD4WS) Electric Vehicle (EV). Electronic differential system can efficiently and effectively replace heavy and inefficient conventional mechanical differential system of a vehicle. The designed ED continuously generates the speed references and steering angle references for each of four wheels individually driven by separate motors. The Controller Area Network (CAN) communication system has been introduced for the purpose of communicating the generated reference by the EDs to the corresponding traction motors and also for the purpose of feeding back the actual data from the wheels back to the EDs. The performance of the proposed ED has been validated through credible MATLAB/Simulink simulations and real time Digital Signal Processor (TMS320F2812) based online simulation. The real time DSP kit also serves the purpose of CAN controller.

Keywords: Controller Area Network, Electric Vehicle, Electronic Differential, 4WD4WS, TMS320F2812.

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Chapter 1

Introduction

1.1 Literature Survey:

In recent years, environmental concerns like global warming, climate change and energy conservation issues have become so critical that many researchers and major vehicle manufacturers have put forth great effort to develop high-performance and low-pollution EVs to replace the conventional vehicles with internal combustion engines (ICEVs). Internal combustion engine vehicles (ICEVs) use fossil fuel as the source of energy in order to generate their propulsion power. Burning of fossil fuels generate greenhouse gases which causes global warming. Besides, their stock is finite and about to finish. For this reason, automotive industry requires alternative drive concepts. Extensive research towards achieving this goal led to the development of EVs. Almost emission free and noise free operation are the merits of EVs, while short range battery backup, lack of recharging stations, long charging time, higher initial cost are the main drawbacks in order to use electric vehicle extensively.

Electric Vehicles, depending upon power conversion types, can be classified into two major categories. These are:

1. Battery Electric Vehicles (BEVs)
2. Hybrid Electric Vehicles (HEVs)

BEVs use battery as the source of electrical energy and that energy will be transformed into mechanical power by means of electric motors only, where as in case of HEVs propulsion of vehicle is due to the combined actions of electric motor and internal combustion engine (ICE). Again depending upon the types and combination of energy converters (electric motors and ICE), HEVs can be classified into various categories: - series hybrid, parallel hybrid, series-parallel hybrid and complex hybrid. The details classifications of EVs have been depicted in fig. 1.1(a).

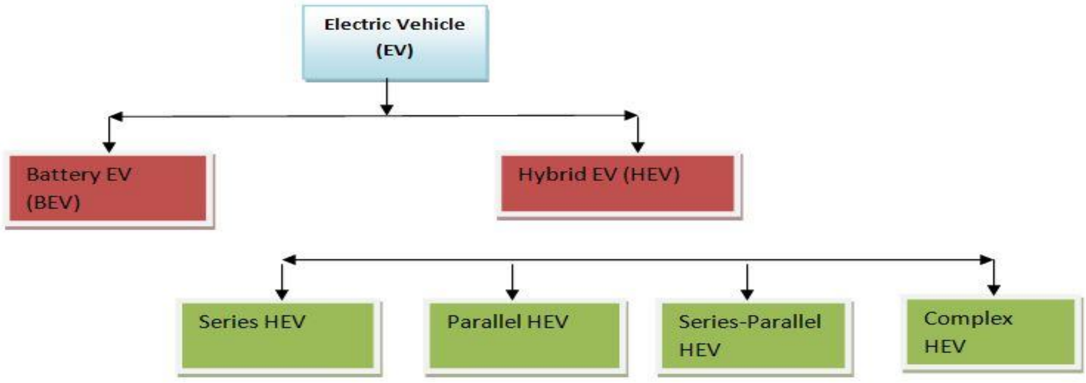


Figure 1.1(a): Classification of EVs

From the perspective of control engineering, the EVs have many advantages over conventional internal combustion engine vehicles [1]:

1) Electric motors can generate fast torque response.
2) Electric motors' torque can be measured precisely.
3) More than one motor can be mounted on each vehicle, and can be controlled independently.

The three major components of electric vehicles are:-

1. Battery for energy storage.
2. Electric motor(s) to drive the wheels.
3. Controllers to control the power supplied to the motor(s).

The design mechanism of EVs follow the same principal as the ICEVs only in this case, the internal combustion engine and the fuel tank can be replaced by the suitable electric motor drive mechanism and battery bank. This is represented in fig. 1.1(b). The mechanical power generated by the motor is transmitted to driving wheels by means of a fixed or changeable gear and a power splitting differential gear (DG) . The motor is fed from the battery through a power converter. Power converters used in EVs allow bi-directional power flow between battery and motor. The backward power flow i.e. from motor to battery is due to regenerative braking and this energy can be stored in the battery [2].

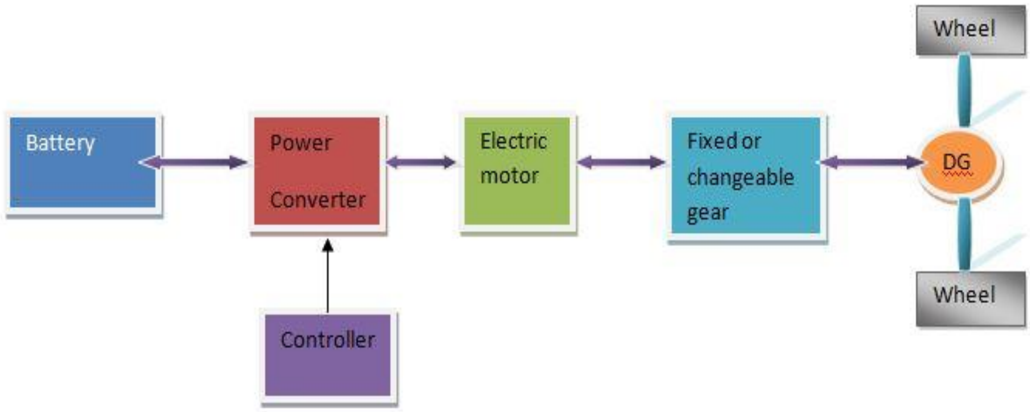


Figure 1.1(b): Basic Block Diagram of an EV

However, in case of pure electric vehicle, the traction motors are placed alongside the driving wheels. Depending upon the set of wheels the driver is driving, EVs can be classified as

1. Front wheel drive
2. Rear wheel drive.

The usual approach is to attach motors only to the set of corresponding driven wheels. However in case of better manoeuvring, motors can be attached to all the four wheels and this is known as Four Wheel Drive (4WD).

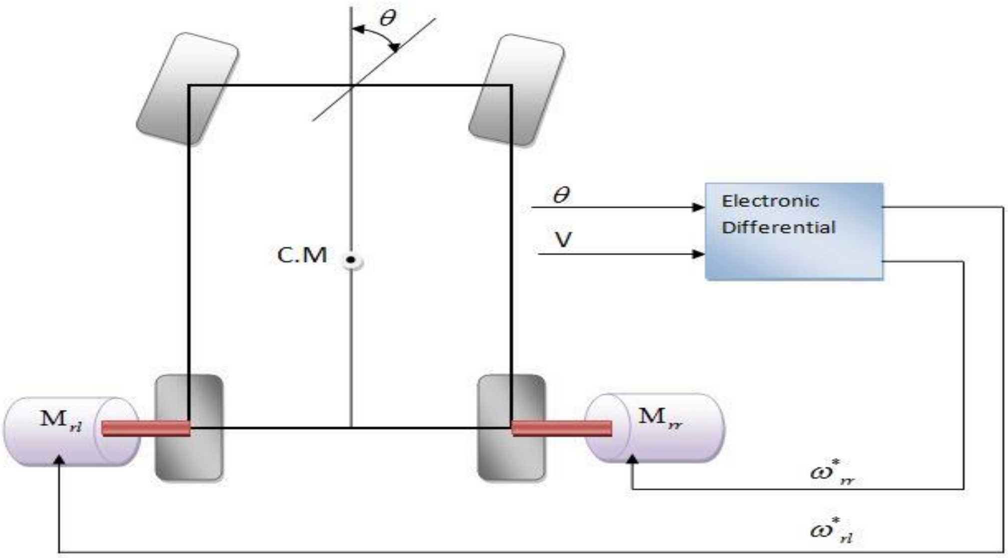


Figure 1.1(c): Electric Vehicle with In-wheel motors and Electronic differential

A rear wheel drive electric vehicle with in-wheel motors and electronic differential has been shown in fig. 1.1(c). An Electronic Differential (ED) which replaces the mechanical gear arrangements is the most important part of an EV and it is used to maintain the speed of each driving wheel separately. Absence of mechanical gear system for transmitting power makes pure electric vehicles very light and more efficient.

Among various components of an electric vehicle, the most important part is electronic differential. The electronic differential system of an EV continuously generates speed references and steering angle references for each of four driving wheels. The function of electronic differential mainly comes into the play when the vehicle is steered. A well designed electronic differential can prevent the vehicle to slip sideways by allowing different wheels of the vehicle to spin at different speeds, particularly when the vehicle follows a curved path.

So far various approaches have been taken to design electronic differential for electric vehicles. Amin Hajihosseinlu et. al. in their work [3], have designed an electronic differential for an electric vehicle with four independent in-wheel motors. Here task of electronic differential is to generate torque references for four wheels based on the inputs: steering wheel angle and acceleration pedal position. Depending upon torque references angular velocity of each wheel will be adjusted. This paper also suggests a simple Yaw control strategy of the vehicle. After tested in MATLAB, the designed ED was tested in a real-time digital simulator, which is then connected to a small motor to verify its performance in hardware-in-loop scheme (HIL).

A well-designed electronic differential can make the vehicle both lighter and more stable in handling. Electric vehicles are expected to have faster torque response than conventional vehicles due to advanced motor-control methods (e.g., direct torque control), which allows the motor to generate rapidly varying amounts of torque [3].

V. Arvind, in his work [4] mainly focuses on the reduction of turning radius of a four wheel steered (4WS) vehicle. In this work the four wheel steering system is analysed based on kinematic approach. Here two types of steering configurations are mentioned. These are same phase and opposite phase configuration namely same phase or positive steering system both front wheels and rear wheels turn in the same direction, where as in case of opposite phase or negative steering system rear wheels turn in opposite direction of the front wheels. After analysing both types of steering system, it is found that for a particular steering angle input, turning radius is smaller in case of opposite phase steering configuration.

M. Schael et. al., [5] in their work tried to develop a concept of novel electric differential which can be used in place of conventional mechanical differential for EVs with distributed motors. They have done their work for two wheel drive (rear wheels) EVs. Geometric coherences for vehicles in cornering under ideal conditions are described by Ackermann-Jeantaud model.

An electric differential system has been proposed for rear wheel drive electric vehicle [1]. In this paper two control loops have been designed, the outer control loop which takes care of the Yaw motion of the vehicle and the inner control loop improve robustness against system uncertainties and road condition. The inner loop is designed in MATLAB/SIMULINK software, performed in a computer, where as performance of the outer control loop is realized with an EPF10KE FPGA (Field Programmable Gate Array) in the fixed point arithmetic format.

Azeddine Draou in his work [6], has designed an electronic differential which offers better stability of vehicle in the curved road. The loosely, heavy, conventional mechanical differential is replaced by small, light electronic differential efficiently. The ED has been designed for a two wheel drive electric vehicle where two permanent magnet synchronous machines (PMSM) are used. Direct torque control method (DTC) has been used to control the speed of each in-wheel motor. Different simulations have been carried out: - vehicle is driven on straight road, driven on straight road with slope and driven over a road curved left and right. The simulation results show good vehicle stability on a curved road.

Use of four independent in-wheel motors provides the opportunity to generate different torque speed references to each wheel separately; this not only gives better differential operation but also has considerable potential to improve yaw-motion stability control [7].
In wheel motor controllers can be designed for various aspects of motion stability such as yaw control, lateral control and anti-skid braking system [8]-[11].
Using the concept of model following control (MFC), Hori et. al [12] developed an electric differential system to minimize the tire slip when vehicle was running on low friction road.
On the basis of an optimal slip ratio controller (SRC), Sado *et al.* [13] designed an ED to improve vehicle stability by maintaining the slip ratio within an ideally specified region. This scheme was exquisite, although it required the information of vehicle speed to estimate the slip ratio.

As reported in [14-16] it is preferable to use vector control technique to improve the dynamic performance of PMSM drives for electric vehicle propulsion. However vector control needs quite complicated coordinate transformations on line to decouple the interaction between flux and torque to provide fast torque control of a permanent magnet synchronous motor. Hence computation is time consuming and real time implementation needs high performance DSP chip. In recent times a new control method, called as Direct Torque Control (DTC) has gained popularity for traction motors, because it can produce fast torque control and does not need heavy online computation [14-16].

While designing an ED, it is necessary to measure steering angle of the vehicle and vehicle's reference ground speed continuously and accurately and to feed these measured values to the ED as inputs. Again speed references and steering angle references generated by the ED must be fed to the controllers of traction motors so that the traction wheels can follow these reference speeds. So it is of utmost importance to have a well designed and efficient communication system. Controller Area Network (CAN) is such a system which is dedicatedly designed for automobiles and through this network various components of a vehicle communicates with each other. A component of a vehicle along with CAN controller can be termed as an Electronic Control Unit or in short ECU.

Weimin Li et. al., in their work [17], have designed Vehicle control units (VCUs) for hybrid electric vehicle (HEV) where the control units will be communicating to each other through Controller Area Network (CAN). In their work, DSP TMS320F2812 has been used as the CAN controller. Real time operation of the DSP based controller has been used to run optimization algorithms for energy management strategy.

1.2 Objective of the Thesis:

The objective of this thesis is to design an electronic differential for a semi-autonomous 4WD4WS electric vehicle in order to offer better stability to the vehicle during cornering. A Semi-autonomous vehicle is one in which the activity of the driver combined with the automatic control actions of various controllers, controls the motion of the vehicle. The command inputs from the driver are essentially vehicle's steering angle and vehicle's reference speed. Depending upon these command inputs the electronic differential system will generate the speed references and the steering angles for each of the four wheels to follow. The Controller Area Network (CAN) communication system has been adopted in this dissertation to communicate the reference signals generated by the ED to the controllers of respective traction motors. The performance of the proposed intelligent ED has been tested in

MATLAB Simulink platform and the CAN communication has been implemented and tested in real time 'Digital Signal Processor' (DSP) TMS320F2812 which serves the purpose of a CAN controller.

1.3 Organization of the Dissertation:

The dissertation is organized as follows:

Chapter 1 : The first chapter introduces the dissertation by giving the literature reviews in details. This is then followed by the objective of the thesis.

Chapter 2: In this chapter differential system of a vehicle has been discussed. Mathematical model of an ED has been developed as per Ackermann steering geometry which has been described in this chapter.

Chapter 3: This chapter provides an overview on Controller Area Network (CAN). The CAN protocol system has been discussed broadly in this chapter. A loopback test for CAN communication has been performed by using TMS320F2812 DSP as a CAN controller.

Chapter 4: In this chapter first results of MATLAB simulation of the proposed ED have been discussed. Then the outputs obtained from DSP TMS320F2812 have been discussed and compared with the outputs from MATLAB simulation.

Chapter 5: This chapter presents the future scope of the work and conclusion.

Chapter 2

Design of an Electronic Differential

For any vehicle, differential system plays an important role when the vehicle is steered. The need of differential system for a vehicle during steering condition can be realised by 'Ackermann Steering Geometry'.

2.1 Ackermann Steering Geometry:

According to Ackermann steering geometry, the four wheels of a vehicle during cornering travel through circular paths of different radii, having a common centre point. It was first proposed by the German carriage builder Georg Lankensperger in Munich in 1817 and then patented by his agent in England, Rudolph Ackermann (1764–1834) in 1818 for horse-drawn carriages. The intention of Ackermann geometry is to avoid the tyres to slip sideways when following the path around a curve.

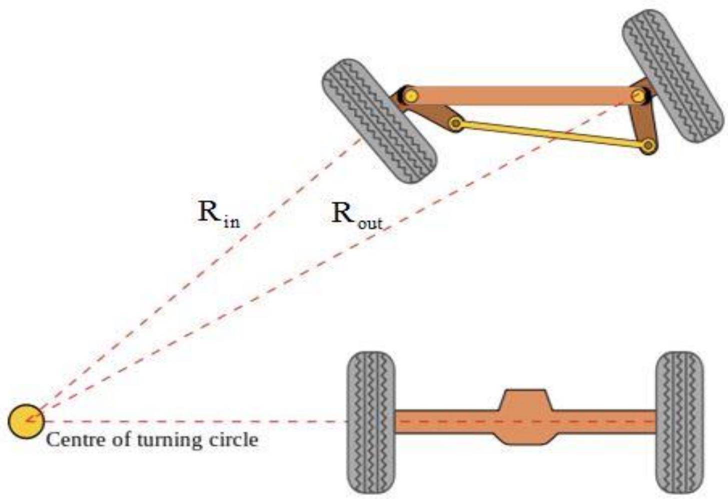


Figure 2.1(a): Ackermann Steering Geometry

The above figure shows the geometry of a vehicle when the vehicle is steered to take a left turn. The moment vehicle is steered all the four wheels of the vehicle start to follow circular paths of different radii. In fig. 2.2(a) 'centre of turning circle' is the common centre point of the four circular paths travelled by four different wheels.

The 'centre of turning circle' is also called as Instantaneous Centre of Motion (ICM). It is named so because the position of this point varies from instant to instant with the variation of steering angle and the vehicle's position. ICM is the intersecting point of the perpendicular to the velocity vectors of the four wheels [18]. For a conventional two wheel steered (front wheel steered) vehicle as the rear wheels are fixed on the axle so the ICM must be lying always on a line extended from the rear axle as shown in the above figure. From this geometry it can also be observed that the inner side wheel must be turned at a greater angle compare to the outer wheel during steering operation of the vehicle.

2.2 Differential System of a Vehicle:

While driver of a vehicle steers the vehicle, the four wheels start to move along circular paths of different radii, having a common centre point. The outer wheel moves along a circular path whose radius is greater than the inner wheel. So, in particular time duration the outer wheel travels more distance compare to the inner wheel and that is why the outer wheel has to move faster than inner wheel. As the linear velocity of outer wheel is greater than inner wheel hence angular velocity of the outer wheel will also be greater than inner wheel, considering both the wheels have same radius which can be proved mathematically with the help of fig. 2.2(a).

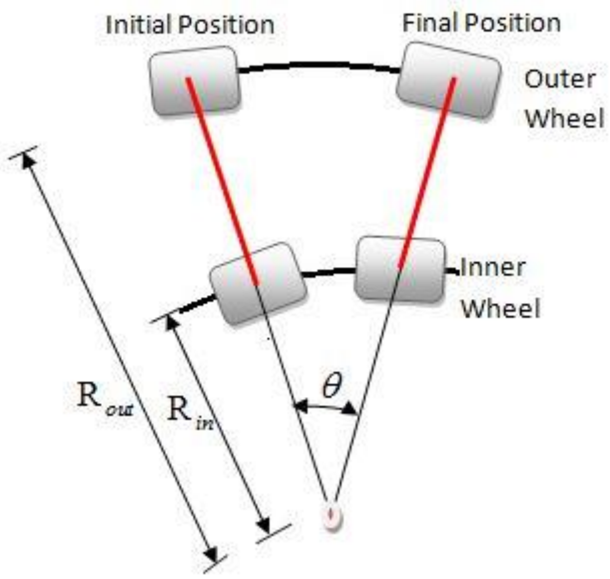


Figure 2.2(a): Front or Rear Set of Wheels of a Vehicle on curved path

The fig. 2.2(a) shows the front or rear set of wheels of a vehicle on a curved path.

In any particular time duration Δt both the inner wheel and outer wheel will make an angle θ (in degrees) at the centre.

Therefore, in that particular time period Δt the outer wheel covers a distance of, $\left(R_{out} \times \theta\right)$

In the same time span, the inner wheel covers a distance of, $\left(R_{in} \times \theta\right)$

Linear velocity of the outer wheel is given as:

$$V_{out} = \frac{R_{out} \times \theta}{\Delta t} \tag{2.1}$$

Linear velocity of the inner wheel is given as:

$$V_{in} = \frac{R_{in} \times \theta}{\Delta t} \tag{2.2}$$

From equation (1) and (2) it can be written as:

$$\frac{V_{out}}{V_{in}} = \frac{R_{out}}{R_{in}} \tag{2.3}$$

$$\Rightarrow \quad \frac{\omega_{out} \times R_w}{\omega_{in} \times R_w} = \frac{R_{out}}{R_{in}} \tag{2.4}$$

$$\Rightarrow \quad \frac{\omega_{out}}{\omega_{in}} = \frac{R_{out}}{R_{in}} \tag{2.5}$$

ω_{out} and ω_{in} are the angular velocities of outer wheel and inner wheel respectively.

R_w is the radius of both wheels.

In fig. 2.2(a) it is seen that the outer wheel travels along the circular path whose radius is larger than the inner wheel's path i.e. $R_{out} > R_{in}$

As $R_{out} > R_{in}$, so from equation (2.5) it can be said that $\omega_{out} > \omega_{in}$

So, during steering of the vehicle the outer wheels rotate faster compared to the inner wheels. Hence, there is a need for an arrangement in the vehicle which will split the engine torque and provide different amount of torque to different traction wheels in order to spin them at different speed. This arrangement is known as differential. Without a differential system, the same speed of inside and outside wheels of a vehicle during steering will cause a serious slip between wheels and ground [19]. The mechanical differential is shown in fig. 2.2(b).

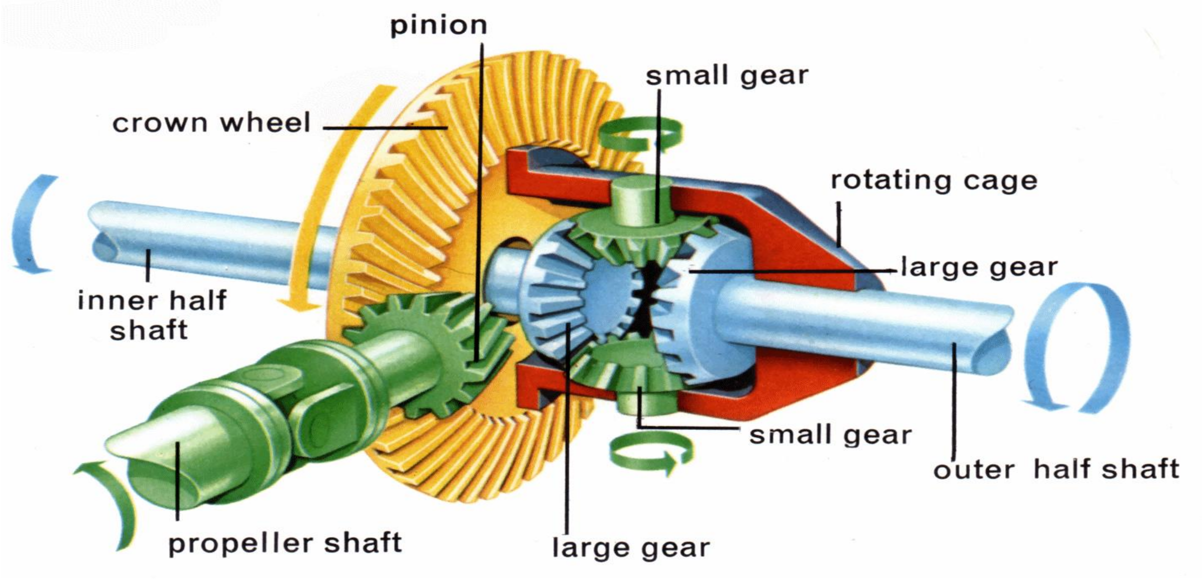


Figure 2.2(b): Conventional mechanical differential

Now a days, electronic differential (ED) is used in place of mechanical differential inside the EVs which use in-wheel motors for propulsion. Depending upon steering angle input from the driver and the reference linear velocity of the vehicle (which comes from accelerator pedal or brake pedal) ED calculates torque references or speed references for the in-wheel motors.

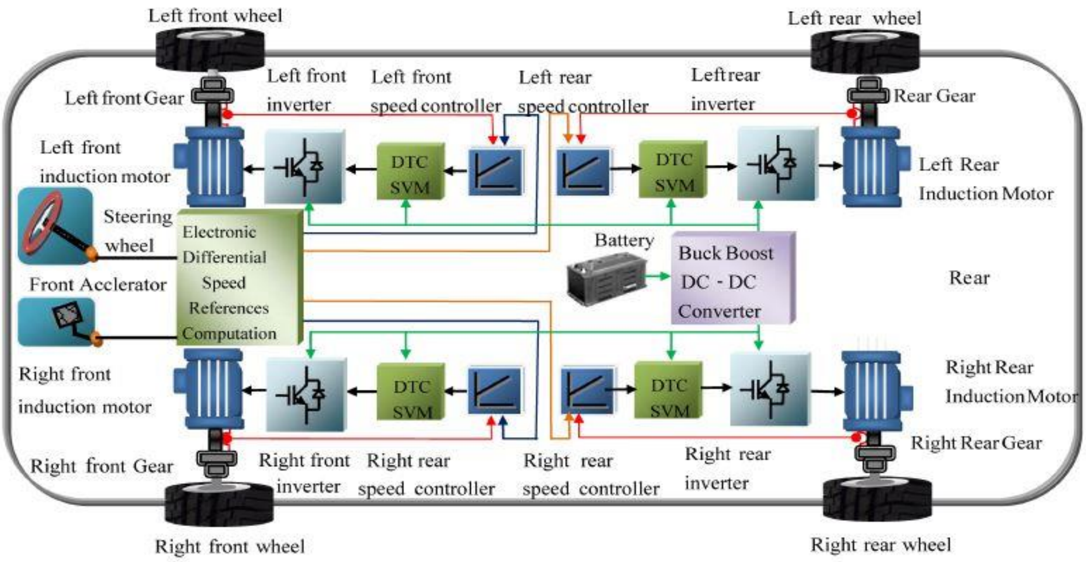


Figure 2.2(c): Electric Vehicle with Electronic differential

Fig. 2.2(c) represents an electric vehicle with electronic differential system. The EV, shown here uses four in-wheel induction motors for its propulsion. As shown in the figure, the ED receives instructions from driver through steering wheel and accelerator pedal and computes the speed references for each of the four induction motors. Direct Torque Control (DTC) method is used for the induction motors such that they can track their corresponding reference speed.

2.3 Mathematical Model of an Electronic Differential:

The kinematic model of a 4WS4WD vehicle during cornering can be developed as per the geometric model proposed by Ackermann and Jeantad [20]. The kinematic model of a vehicle while taking a left turn is shown in the fig. 2.3(a). Here the steering system of the vehicle is such that during cornering, front set of wheels and rear set of wheels are steered opposite to each other.

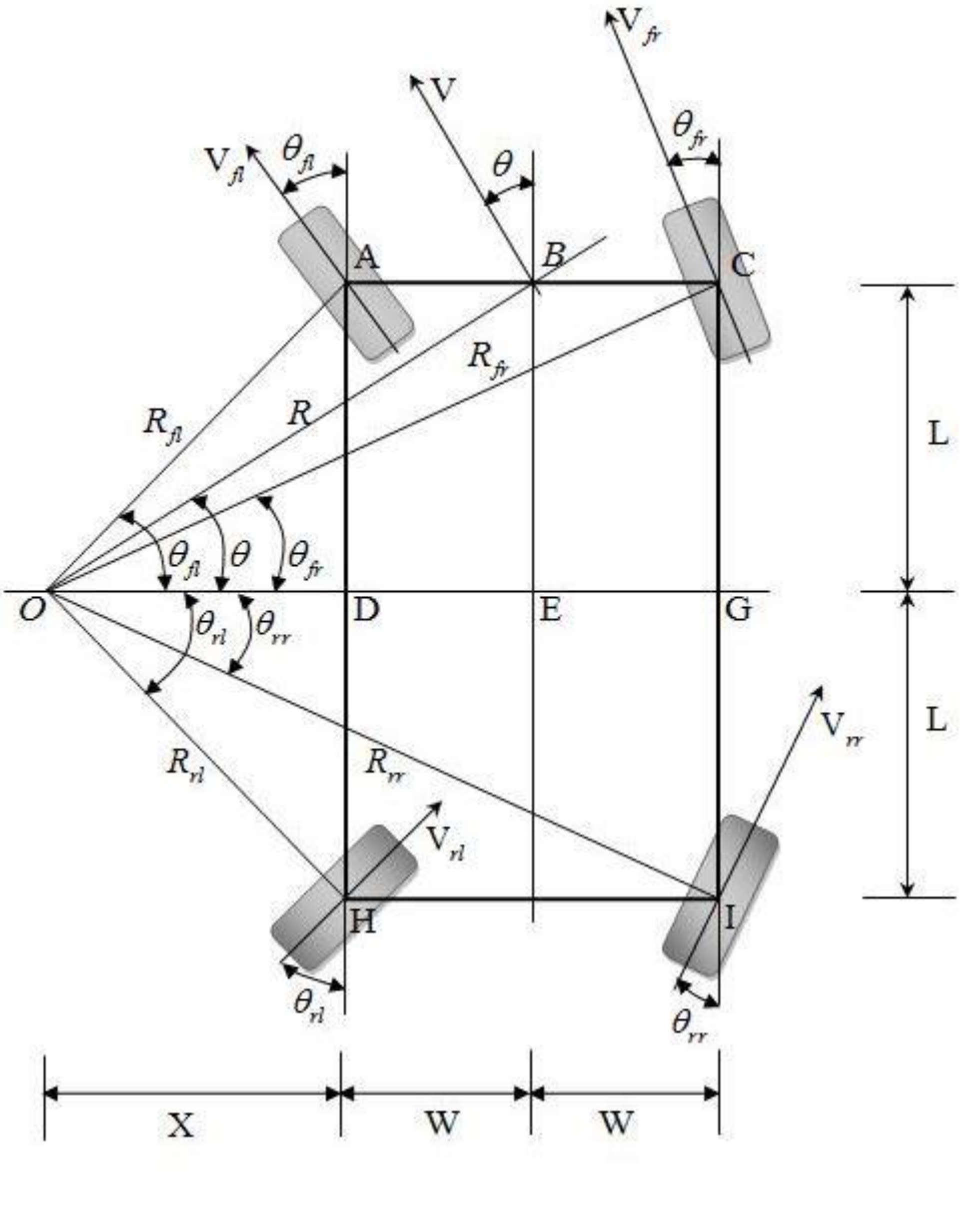


Figure 2.3(a): Kinematic Model of a Vehicle During Left Cornering

In fig. 2.3(a), O is the instantaneous centre of motion (ICM).

Vehicle length = 2L, Wheel base = 2W.

θ is the steering angle of the vehicle.

θ_{fl} is the steering angle for front left wheel.

θ_{fr} is the steering angle for front right wheel.

θ_{rl} is the steering angle for rear left wheel.

θ_{rr} is the steering angle for rear right wheel.

R_{fl} is the turning radius of front left wheel.

R_{fr} is the turning radius for front right wheel .

R_{rl} is the turning radius for rear left wheel.

R_{rr} is the turning radius for rear right wheel.

R is the turning radius of the vehicle.

'E' is the centre of mass (C.M) of the vehicle. (Considered that, total mass of the system is uniformly distributed).

V is the ground speed of the vehicle at point B, depending upon which the velocities of the four wheels will be calculated.

From $\triangle$OBE we get,

$$\tan\theta = \left(\frac{L}{X+W}\right) \tag{2.6}$$

$$\sin\theta = \frac{L}{R} \tag{2.7}$$

From equation (2.6) we get,

$$X = \left(L \times \cot\theta - W\right) \quad (2.8)$$

From equation (2.7) we get,

$$R = L \times \operatorname{cosec}\theta \quad (2.9)$$

θ is measured continuously, values of L and W are known. So, real time values of X and R can be obtained from equation (2.8) and (2.9) respectively.

From ΔOAD we get,

$$\tan\theta_{fl} = \left(\frac{L}{X}\right) \quad (2.10)$$

$$\Rightarrow \theta_{fl} = \tan^{-1}\left(\frac{L}{X}\right) \quad (2.11)$$

$$\text{and, } R_{fl} = \sqrt{(L^2 + X^2)} \quad (2.12)$$

From, ΔOCG we get,

$$\tan\theta_{fr} = \left(\frac{L}{X + 2W}\right) \quad (2.13)$$

$$\Rightarrow \theta_{fr} = \tan^{-1}\left(\frac{L}{X + 2W}\right) \quad (2.14)$$

$$\text{and, } R_{fr} = \sqrt{L^2 + \left(X + 2W\right)^2} \quad (2.15)$$

From ΔOHD we get

$$\tan\theta_{rl} = \left(\frac{L}{X}\right) \quad (2.16)$$

$$\Rightarrow \theta_{rl} = \tan^{-1}\left(\frac{L}{X}\right) \quad (2.17)$$

and, $R_{rl} = \sqrt{L^2 + X^2}$ (2.18)

From Δ OGI we get,

$$\tan\theta_{rr} = \left(\frac{L}{X+2W}\right) \quad (2.19)$$

$$\Rightarrow \quad \theta_{rr} = \tan^{-1}\left(\frac{L}{X+2W}\right) \quad (2.20)$$

And, $R_{rr} = \sqrt{L^2 + (X+2W)^2}$ (2.21)

Now, linear velocities of each wheel can be written in terms of ground speed of vehicle (V) at point B.

$$V_{fl} = \left(\frac{V \times R_{fl}}{R}\right) \quad (2.22)$$

$$V_{fr} = \left(\frac{V \times R_{fr}}{R}\right) \quad (2.23)$$

$$V_{rl} = \left(\frac{V \times R_{rl}}{R}\right) \quad (2.24)$$

$$V_{rr} = \left(\frac{V \times R_{rr}}{R}\right) \quad (2.25)$$

Now, assume that radius of each wheel is R_W .

So, angular velocities of the four wheels can be written as,

$$\omega_{fl} = \left(\frac{V_{fl}}{R_W}\right) \quad (2.26)$$

$$\omega_{fr} = \left(\frac{V_{fr}}{R_W}\right) \quad (2.27)$$

$$\omega_{rl} = \left(\frac{V_{rl}}{R_w} \right) \tag{2.28}$$

$$\omega_{rr} = \left(\frac{V_{rr}}{R_w} \right) \tag{2.29}$$

$\omega_{fl}, \omega_{fr}, \omega_{rl}, \omega_{rr}$ are ED generated reference angular velocities for front left, front right, rear left, rear right wheel respectively.

$\theta_{fl}, \theta_{fr}, \theta_{rl}, \theta_{rr}$ are ED generated reference steering angle for front left, front right, rear left, rear right wheel respectively.

This way, ED calculates steering angle as well as desired angular velocity for each wheel. These values of steering angle and velocities are fed to the controllers of respective motors as reference inputs.

It can be observed from the above mathematical model that the two left wheels (left front and left rear) are steered at equal angle and their speeds are also equal. The same is true for the two right wheels.

The major assumption which has been made here for the designing of the ED is the zero slip angle of the wheel. This means velocity vectors of the wheels will be aligned in the direction of orientation of the respective wheels.

2.4 Operation of Electronic Differential using CAN communication:

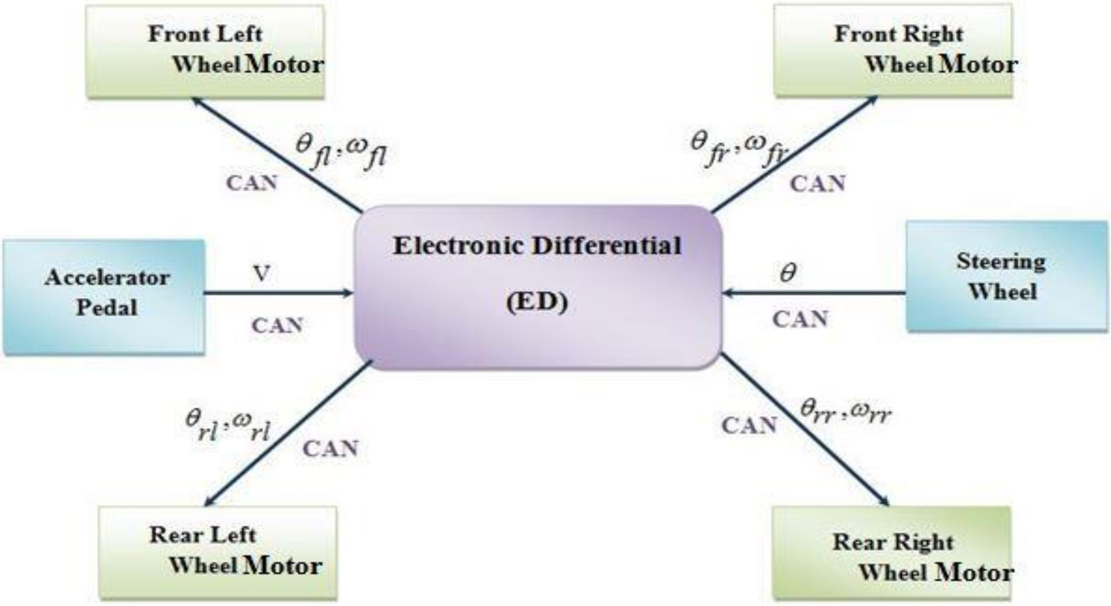


Figure 2.4(a): Schematic of Electronic Differential System

In the above figure, a schematic of proposed ED has been presented. As already discussed, the purpose of electronic differential system is to generate speed references and steering angle references for the wheels of a vehicle. The ED calculates these speed and steering angle references for the wheels based on instantaneous steering angle and the reference ground speed of the vehicle given as an input to the accelerator pedal by the driver. In a semi-autonomous vehicle, steering angle and reference linear velocity are given by the driver. The driver sets the steering angle of the vehicle using steering wheel and reference linear speed of the vehicle is set by the driver through accelerator or brake pedal. The generated speed references and steering angle references are transmitted to the respective controllers of the traction motors. Fig. 2.4(a) shows the various components associated with the ED. It is quite obvious that the entire control methodology of the semi-autonomous vehicle will function properly if all the components are connected to the ED either by wired network or on shared wireless network and share their information with one another. The different components like accelerator or brake pedal, steering wheel and the four traction motors shown in figure, comes along with microcontrollers and hence they can be considered as Electronic Control Units or ECUs. Controller Area Network or CAN communication systems can be used with great efficiency and effectiveness for the communication of these ECUs. When these ECUs will be able to communicate successfully over the network then the ED will function accurately. Hence, the next section of this dissertation will extensively discuss the basics of CAN communication system.

Chapter 3

Controller Area Network (CAN)

3.1 An Overview:

CAN which is the abbreviation of Controller Area Network, is a multi master serial communication system specially designed for automobile industry. CAN was first developed by German automotive system supplier Robert BOSCH in mid-1980s for automotive applications as a method for enabling robust serial communication [21]. The goal was to make automobiles more reliable, safe and fuel-efficient, while decreasing wiring harness, weight and design complexity.

Unlike a traditional network like USB or Ethernet, CAN does not send large blocks of data 'point to point' under the supervision of a central bus master. In case of CAN all the nodes present in the system are connected through a common bus. So they can communicate each other without the supervision of a host computer. Fig. 3.1(a) represents the schematic.

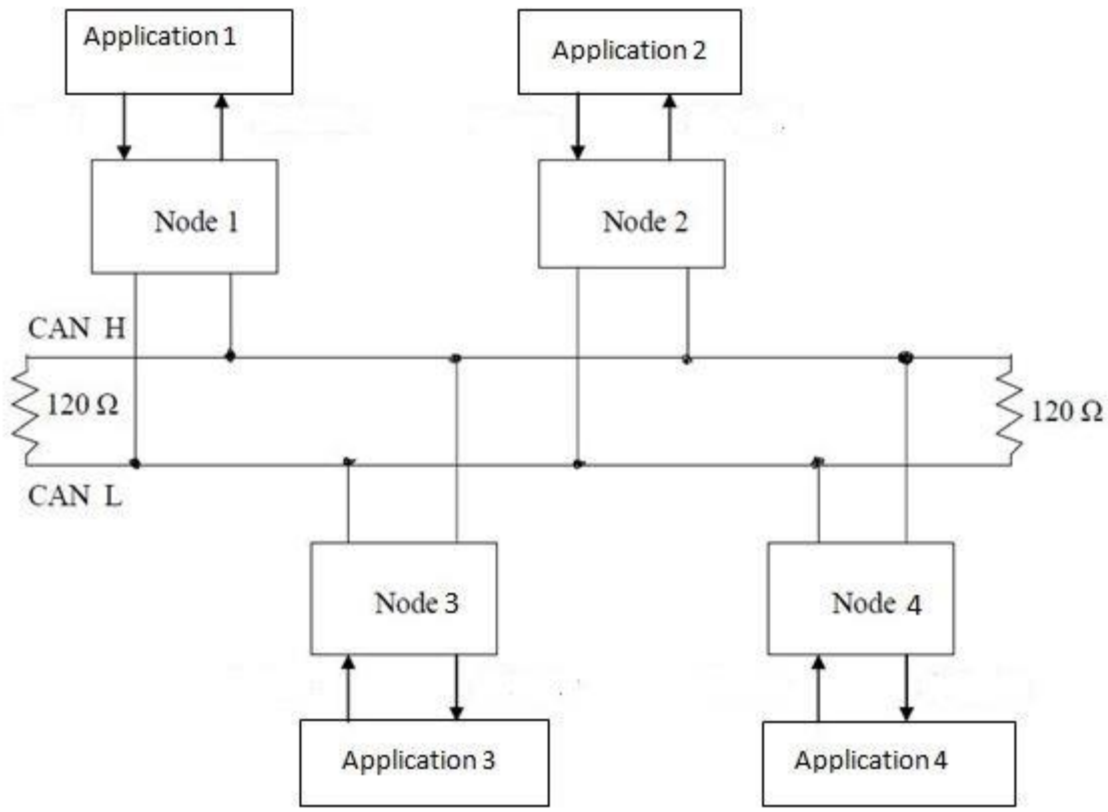


Figure 3.1(a): Schematic of a CAN Network.

As CAN is a multi master communication system so every node in the network can function independently. Any node can send messages to the bus and receive messages from the bus. Fig. 3.1(b) shows the various components of a CAN node.

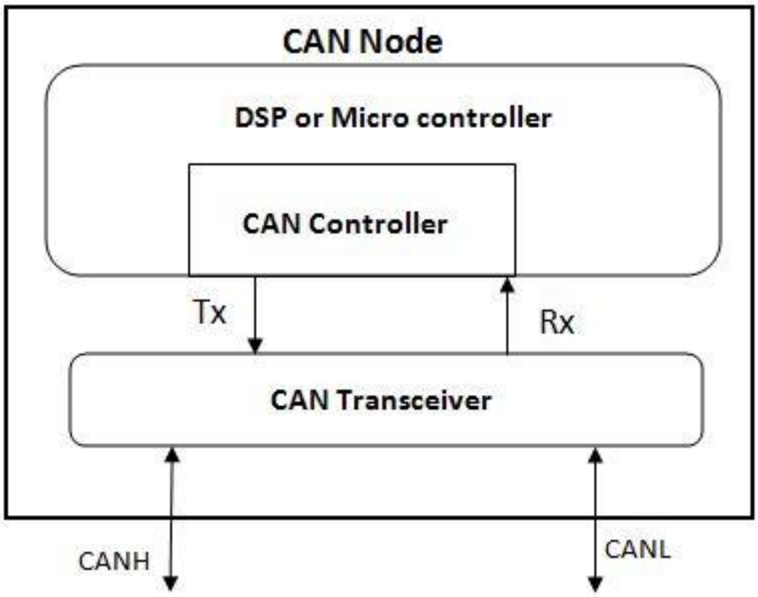


Figure 3.1(b): A CAN node.

Each CAN node essentially consists with:

1. A CAN controller.
2. A transceiver.

The CAN controller provides an interface between the application and the CAN bus. In case of data transmission, first the application sends data to the CAN controller. The function of CAN controller is to convert the data provided by the application into a CAN message. Now, the controller sends this message to the 'transceiver' as serial bit stream and the transceiver converts it into a differential signal. This differential signal is transmitted physically across the CAN bus [22].

CAN bus is a two line bus- CAN High and CAN Low. Physically they are twisted pair of wires. There must be terminating impedance of 120 ohms between CAN high and CAN Low at the both ends of the bus. This restricts the signal from reflections at the end of the bus and ensures the bus gets correct voltage levels [22].

CAN does not use physical addresses to address stations. Instead of using physical addresses, each message is transmitted with an identifier which is recognized by other nodes. The identifier has two functions- it tells about the priority of the message and it is used for message filtering. Whenever a message is available in the CAN bus, every node connected with the bus sees the message but checking the identifier of the message, a node understands whether this message should be received or not. This way the identifier helps in message filtering. Again, when two or more nodes try to send messages at the same time then message with higher priority will be transmitted first and the identifiers of the messages make this priority. CAN uses an arbitration technique in which priority of accessing the bus of a node is determined. In this technique value of identifier of a message is checked and in a situation when more than one node try to send message at a time then the message which has lower value of identifier will be delivered first i.e lower the value of identifier, higher the priority of message.

As per CAN specification there is two logic states. Logical 0 is termed as ‘dominant bit’ where as logical 1 is termed as ‘recessive bit’. For high speed CAN (ISO 11898) physical voltage levels for recessive and dominant bit is shown fig. 3.1(c).

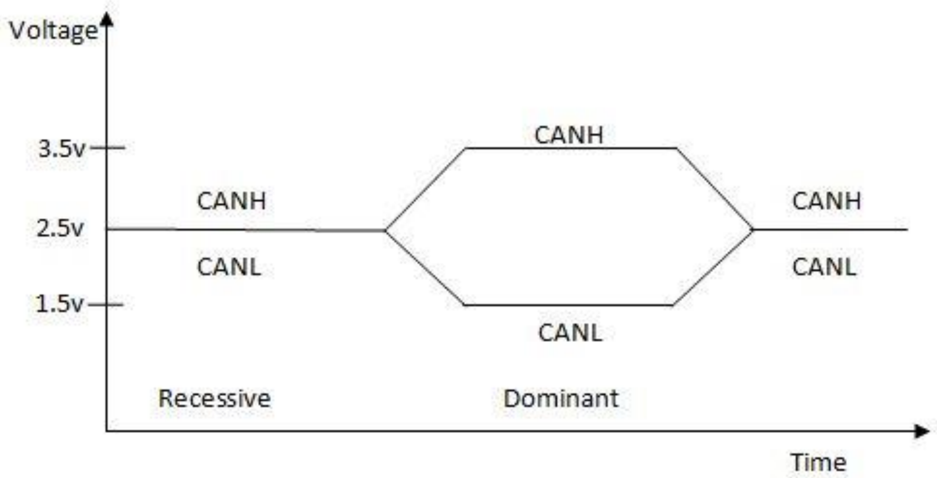


Figure. 3.1(c): Recessive and Dominant Bits of CAN

The physical voltage depending upon logic 1 or 0 is decided is the differential voltage between CANH and CANL.

This protocol allows bit rates up to 1MBPS (Mega bit per second) for network length below 40 m. Longer network distance decreases the bit rate (e.g., 500m at 125 Kbit/sec.) [23]-[24].

3.2 CAN HISTORY:-

CAN was first introduced by a German company Robert Bosch GmbH in 1986. The first CAN controller chips, produced by Intel and Philips, came on the market in 1987. The 1988 BMW 8 series was the first production to feature CAN based wiring system. So far Bosch has published several versions of CAN, and the latest one is CAN 2.0 published in 1991. This specification has two parts: part 'A' is for the standard format with 11 bit identifier where as part 'B' is the extended format with 29 bit identifier. The automotive industry quickly adopted CAN and, in 1993, it became the international standard known as ISO 11898.

3.3 CAN LAYERS:

CAN protocol comprises with two layers: Data Link Layer (DLL) and Physical Layer. Data link layer again comprises of two sub layers: Logic Link Layer (LLL) and Medium Access Control (MAC) [22].

The CAN Data Link Layer controls the message communication. The Data Link Layer builds data frames to hold data and control information. It also provides other services such as frame identification, bus arbitration, bit stuffing, error detection, error signalling, fault confinement and automatic retransmission of erroneous frames.

The CAN Physical Layer is responsible for transfer of data between different nodes in a given network; it defines how signals are transmitted and therefore deals with issues like encoding, timing and synchronization of the bit stream to be transferred.

The application layer is specified by higher layer protocols such as CAL/CANOpen and CAN Kingdom, DeviceNet. The CAN ISO standard discussed in this thesis is specified by ISO 118981, which gives the data link layer and the physical signalling, and ISO 118982, which specifies the high speed physical layer characteristics. The different layers are shown in Table 3.1.

Table 3.1: CAN protocol ISO layered model [22].

Data Link Layer (DLL)	**LLC (Logic Link Layer)** Acceptance Filtering Overload Notification Recovery Management **MAC (Medium Access Control)** Data encapsulation Stuffing/de-stuffing Bus Arbitration Error detection Error handling Fault confinement Acknowledgement
Physical Layer	**Physical Signalling** Bit Encoding/decoding Bit timing Synchronization **MDI (Medium Dependent Interface)**

3.4 Data Transmission:

CAN protocol is designed for short length messages. It allows only 0-8 bytes of data in a message. This protocol uses CSMA/CD+AMP (Carrier Sense Multiple Access/ Collision Detection with arbitration on message priority) [25]. Thus this protocol is message oriented and each message has a specific priority according to which it gains access to the bus in case when two or more nodes try to transmit messages at the same time. As per this protocol an ongoing transmission is never interrupted. When the bus is in idle state any node can access the bus but in the event of multiple accesses, priority of the messages is decided by lossless bitwise arbitration method. This method is lossless which means the winner of the arbitration can continue its transmission without restarting it from beginning.

Arbitration is performed during the transmission of identifier field. Each CAN message has an identifier field of 11 bits or 29 bits. As stated earlier, this identifier field is used for message filtering and priority selection. The protocol is so designed that all the nodes connected to the bus are bound to listen to the bus all time which means always every node receives the information that is available on the bus. During arbitration each transmitting node compares the received bit from the bus with its transmitted bit. If a dominant bit is received when a recessive bit is transmitted then the corresponding node loses arbitration. Then the node which has lost arbitration stops the transmission immediately and waits for the end of ongoing transmission. Once the bus is free again another round of arbitration is performed and message with highest priority gets through. The CAN protocol requires that a specific identifier is sent only by one node this ensures that no two messages with the same identifier contend for bus access. Fig. 3.4(a) shows arbitration method for an 11 bit identifier (ID) CAN network.

	Start bit	ID Bits											The Rest of the Frame
		10	9	8	7	6	5	4	3	2	1	0	
Node A	0	0	0	0	0	0	0	0	1	1	1	1	
Node B	0	0	0	0	0	0	0	1	Stopped Transmitting				
CAN data	0	0	0	0	0	0	0	0	1	1	1	1	

Figure 3.4(a): Bus Arbitration Process

The above fig. represents a network with two nodes – node A and node B. Node A and node B are trying to transmit messages at the same time having IDs 00000001111 and 00000011001 respectively. Each node will first transmit the start bit and then transmit first six zeros of their IDs with no arbitration decision being made. But after that, node B transmits a '1' (recessive bit) where as node A transmits a '0' (dominant bit). Now, the recessive bit is overwritten by the dominant bit and it appears as '0' on the bus. when this happen, node B knows that it transmitted a recessive bit but it sees a dominant bit on the bus then it realizes that there is a collision and lost arbitration. Node A which has won the arbitration, continues its transmission without any data loss. It should be noted that during data transmission MSB is transmitted first.

3.5 CAN Message Types:-

CAN protocol supports four frame types:

1. Data frame: contains node data for transmission.
2. Remote frame: send request for the transmission of a specific identifier.
3. Error frame: a frame transmitted by any node detecting an error.
4. Overload frame: a frame to inject delay between data and or remote frame.

3.5.1 DATA FRAME:-

It is used to transmit data over network. A data frame can support up to 8 bytes of data. A data frame composed of eight different bit fields: start of frame (SOF), arbitration field, control field, data field, CRC field, Acknowledgement field (ACK field), end of frame (EOF), and the inter frame space (IFS).

The CAN protocol specifies two versions of the Frame, the Base Format and the Extended Format. The CAN specification 2.0A defines the Base Format CAN systems where the frames have standard 11 bit identifiers while the CAN specification 2.0B defines the Extended Format CAN systems where frames have 29 bit identifiers. The extended format is used in complex systems with heavy traffic where the number of messages created by transmitters on the network is greater than the number of possible ID codes that the CAN system could assign to them to make sure that each message is unique. In standard format only 2048 unique identifiers are possible where as using extended format 537 million unique identifiers are possible. Data frame for standard and extended format have been shown in fig. 3.5(a) and 3.5(b) respectively.

Figure. 3.5 (a): CAN Data Frame for Standard (11 bit identifier) Format

Bit length of various fields of a standard data frame is shown below in Table 3.2.

Table 3.2: Various Fields of a Data Frame for Standard Format

Field	No. of Bits	Field	No. of Bits
Start of Frame(SOF)	1	CRC	15
Identifier	11	CRC delimiter	1
RRT	1	ACK slot	1
IDE	1	ACK delimiter	1
Reserved (r0)	1	EOF	7
DLC	4	Inter Frame Space(IFS)	3
Data field(0-8 bytes)	0-64		

Figure. 3.5(b): CAN Data Frame for Extended (29 bit identifier) Format.

Bit length of various fields of a standard data frame is shown below in Table 3.3.

Table 3.3: Various Fields of a Data Frame for Extended Format.

Field	No. of Bits	Field	No. of bits
SOF	1	Data length code(DLC)	4
Identifier A	11	Data Field	0-64
Substitute remote request (SRR)	1	CRC	15
IDE	1	CRC delimiter	1
Identifier B	18	ACK slot	1
RTR	1	ACK delimiter	1
Reserved bits (r1, r0)	2	EOF	7

The various fields of data frame are explained below.

SOF: Logic '0' or dominant state of this field indicates initiation of a message transmission. The CAN bus is in idle (recessive) state prior to the transmission of this bit. All the nodes connected to the bus receive this bit and synchronize their clock to the transmitter's clock.

Arbitration field: This field is of 12 bits, (for standard format) in which 11 bit is used for message identifier and one bit is used as remote request bit (RTR) bit.

11 bit message identifier has two functions:

1. Select the priority of a message.
2. Message filtering.

Lower the value of identifier, higher is the priority of message.

The RTR bit indicates whether the frame is a data frame or a remote frame. Generally data transmission is performed on an autonomous basis with the data source sending out a data frame. It is also possible, however, for a destination node to request the data from the source by sending a remote frame. For a data frame this RTR bit must be dominant. When RTR bit is recessive i.e logic '1' it indicates to a remote frame. There will be no data field in a remote frame. A node on the reception of a remote frame, initiates the transmission of a data frame.

In the event of a Data Frame and a Remote Frame with the same identifier being transmitted at the same time, the Data Frame wins arbitration due to the dominant RTR bit following the identifier.

Control field: control field is made up of six bits: identifier extension bit (one bit), reserved bit (one bit), data length code bits (4 bits).

Identifier extension bit (IDE) must be transmitted as dominant bit in standard format to indicate that there is no more identifier bits in the message. Reserved bit (r0) , transmitted as dominant bit. The last four bits i.e data length code (DLC) contains the information about the number of bytes in data field. The admissible value of the DLC field varies between zero to eight. When the value of this field is greater than eight; this will be considered as eight only.

Data field: This field contains the actual information to be transmitted. This field is of variable length. The data field can contain up to 8 bytes of data. Data is transmitted serially with the MSB first.

CRC field: This field is made up of 15 bit CRC sequence and the recessive CRC delimiter bit. The receiver uses the CRC sequence to check if the data bit sequence in the frame was corrupted during delivery.

Acknowledgement field: this field is of 2 bits and contain one ACK slot bit and one ACK delimiter bit. A transmitter node always transmit a recessive ACK slot bit, any receiver on successful reception of the message send back a dominant bit in order to acknowledge the successful reception of the message. A transmitter on reading back a dominant bit in the Acknowledgement Slot understands that at least one node has received a complete and error free message. ACK delimiter bit is always recessive.

EOF: This field in a data frame is used to indicate the end of message. This field contains seven successive recessive (logic '1') bits.

Inter Frame Space: Every Data or Remote Frame is separated from the preceding frames by the Inter Frame Space. The IFS is made up of a sequence of recessive bits which extends for at least 3 bit durations. The bus may continue to remain idle after this, or a new frame will be indicated with the dominant Start of Frame bit. If one of the first two bits of this field is dominant then it is assumed an Overload Frame has been initiated.

3.5.2 Remote Frame:-

Remote requests are sent out on a regular basis to get updates from other nodes. This feature is very useful in situation where a node which was temporarily offline wishes to reconnect to the network. The node might have information that is not up to date. In such a case the node need not to wait until the corresponding transmitters send messages.

Any node in the CAN network can send a 'Remote Frame' to the bus in order to get information from other nodes. Every other nodes on the network on the reception of remote transmission request (RTR) reads the identifier of the frame in order to check whether this request is relevant to it or not. Then the nodes for which the request of transmission was sent , will initiate the transmission of data frame. The request and reply are two different frames on the bus. Reply of the request can be delayed by the arbitration process in addition to the possible delay by the application. An advantage of this feature is that the message by the transmitter containing the application data is not only received by the requesting receiver but also possible by other receivers which are interested in this message. This mechanism ensures the data consistency of the network.

Structure of data frame and remote frame are similar the only difference is that RTR bit is 'recessive' (logic '1') for remote frame, where as it is 'dominant' (logic '0') in case of data frame. There is no Data Field, independent of the values of the Data Length Code which may be signed any value within the admissible range 0 to 8.

3.5.3 Error Frame:-

Whenever a CAN node detects an error, signals the presence of error by sending out an Error Frame. The Error Frame can be sent at any point of a transmission and always send before the completion of transmission of Data Frame or Remote Frame. The node which is transmitting Data Frame or Remote Frame , constantly monitors the bus. When the transmitter node detects the error frame, it aborts the current transmission and resend the message once the bus is free.

The Error Frame consists of two different fields: the first field is given by the superposition of Error Flags (6-12 dominant/recessive bits) contributed from different stations, the second field is the 8 bits (recessive) Error delimiter.

Error Flag: error flag is of two types:

Active Error Flag: This flags are made up of six consecutive dominant bits. This sequence violates the rule of bit stuffing. Total length of this flag varies between 6 to 12 bits. This is due to the superposition of different error flags transmitted by individual nodes.

Passive Error Flag: Passive error flags are made up of six consecutive recessive bits.

Error Delimiter:- The Error Delimiter consists of 8 recessive bits. After transmission of an error flag, each node sends recessive bits and monitors the bus until it detects a recessive bit. It then starts transmitting 7 more recessive bits.

3.5.4 Overload Frame:-

An overload frame is generated by a node, when this node is unable to process the received message. The structure of overload frame is quite similar to the active error flag, the only difference is that an overload frame is initiated at the end of EOF field or the IFS field. A node which is facing problem with the processing of last received message sends an overload frame to delay the transmission of messages by other nodes. Then all of the nodes present in the system see a sequence of eight successive recessive bits on the bus and after that they again contend for bus access.

3.6 ACK Slot:-

The ACK slot is used to acknowledge the reception of a valid CAN frame. Each node that receives an error free CAN message transmit a dominant bit in the ACK slot and thus overrides the recessive bit of the transmitter. If the transmitter sees a recessive level in the ACK slot then it knows that no receiver found a valid CAN frame.

A receiving node may transmit a recessive bit to indicate that it did not receive a valid frame where as other node may receive the frame without finding any error, then second node transmit a dominant bit. This dominant bit overrides the recessive bit. in such case the transmitter cannot know whether the message has been received by all other nodes or not.

3.7 Inter Frame Space:

Data and remote frames are separated from preceding frame of any type by a field which is termed as Inter Frame Space (IFS) field.

During intermission no node is allowed to start the transmission of a new frame. Intermission field contain three recessive bits.

Bus Idle condition is recognized as free bus, having arbitrary length. At this stage any node can access the bus and start the transmission of a frame by sending a dominant bit (SOF).

3.8 Error Process:

The robustness of CAN may be attributed in part to its extensive and sophisticated error checking procedures. Every error that is detected by a network node will be notified to the rest of the network immediately. There are several mechanisms in the CAN protocol, to detect errors and to prevent erroneous nodes from disabling all bus activities. The CAN error process is divided into three parts: Error Detection, Error Handling, and Error Confinement.

The CAN protocol is so designed that whenever a node detect any error in a transmitted message, immediately it signals to other nodes (including transmitter node) about the error by sending an error frame.

A CAN network deals with an error in three steps: Error detection, Error handling, and Error confinement.

3.8.1 Error Detection:

Mechanisms which are used in CAN protocol in order to find errors are described below:

Cyclic Redundancy Check: The CRC Field of every message holds the checksum of the transmitted data. This CRC sequence is transmitted in the CRC Field of the CAN frame. The receiving node performs a similar checksum of the received application data and performs a comparison to the received sequence. If the receiver detects a mismatch between the calculated and the received CRC sequence, then a CRC error has occurred. The receiver discards the message and transmits an Error Frame to request retransmission of the frame.

Form Check: As per CAN protocol there are certain predefined bit values which must be transmitted recessive. If a receiver detects a dominant bit in one of these positions, a form error will be flagged. These are CRC delimiter, ACK delimiter, and the EOF bits.

Acknowledgement Check: If a transmitter does not see a dominant bit in the ACK slot then it understands that none of the nodes connected in the system has received the message successfully.

Bit monitoring: As said before during transmission of a frame, the transmitter node also monitors the bus. Now if the transmitter sees a different bit level compare to its transmitted value (except during arbitration), an error is flagged.

Bit Stuff Monitoring: The bit stuffing rule specifies that a bit of opposite polarity is inserted after every five consecutive bits of the same polarity. If any receiving node detects six consecutive bits of the same polarity between Start of Frame and the CRC Delimiter, the bit stuffing rule has been violated. A stuff error occurs and an Error Frame is generated. The message is then resend.

3.8.2 Error Handling:

A CAN node on detection of an error sends an Error Frame to the bus. Due to this Error Frame, the transmitter node aborts the ongoing transmission and other participating nodes discard the erroneous message and wait for the retransmission of it. This way any error is handled and data consistency is ensured throughout the network.

3.8.3 Error Confinement:

The probability of a network breakdown because of a local disturbance of one or a group of network nodes is very high. The CAN protocol makes use of a unique algorithm to prevent such a scenario. The algorithm is designed to automatically detect a faulty node and disconnect it from the network by removing the nodes transmit capability on reaching an error limit.

To implement error confinement mechanism, CAN makes use of two error counters, one to keep track of transmit errors (transmit error counter) and other to track of receive errors (Receive error counter).

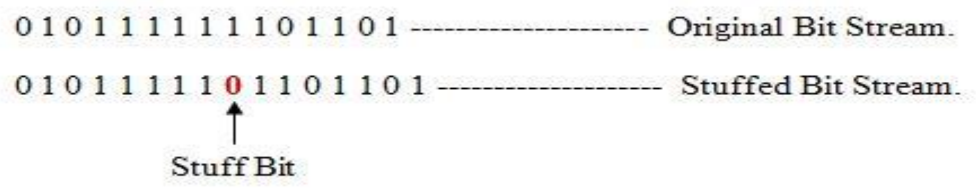
3.9 Bit Stuffing:

The practice in which a bit of opposite polarity is added after the transmission of five consecutive bits of same polarity is known as Bit stuffing. Due to Non Return to Zero (NRZ) coding used with CAN, bit stuffing is necessary. The protocol is so designed that the receiver which has received a frame having stuff bits, can process the message by neglecting the stuff bits [25].

The frame segments Start of Frame, Arbitration Field, Control Field and CRC sequence are coded by the method of bit stuffing. The remaining bit fields of the data frame or remote frame the CRC delimiter, ACK field and EOF are fixed form and are not stuffed. The Error Frame and the Overload Frame are of fixed form as well, and are not coded with bit stuffing.

Bit stuffing method is also significant due to the error signalling mechanism of CAN. As per the protocol transmission of six consecutive bits of same polarity indicates an error frame which is transmitted by a node to signal other nodes that there is something wrong in the ongoing transmitted message. Therefore, if a node try to transmit a message where there is six or more than six consecutive bits of same polarity, without use of stuff bit transmission of message is not possible.

Suppose a bit stream of 010111111101101 to be transmitted serially through a channel. Then the original bit stream without bit stuffing and with bit stuffing is shown below.



3.10 CAN Applications:

Though CAN was initially designed for automotive purposes but now a days it is extensively used in industries, entertainment, medical devices. The modern automobile may have as many as 70 electronic control unit (ECU) for various subsystems. The biggest processor is the engine control unit and others are used for power transmission, audio system, power window, antilock braking system, airbags, electric power steering, recharging system of battery etc.. Inorder to get better comfort, reliability, economic operation, the various subsytems should communicate with each other. The CAN standard was designed to fill this need.

3.11 Loopback Test Using eZdspF2812:

Loopback test is performed when there is only one node present in the network. Node transmits data to itself and receives it. In this project an loopback test has been performed using eZdsp board which uses ‘TMS320F2812’ processor which supports CAN 2.0 B . CCS gives a platform to the users to interact with the processors. Code Composer Studio (CCS) is used as an integrated development environment for Texas Instruments’ product .In order to perform this loop back test first simulink model had been developed in MATLAB, then corresponding ‘C’ code has been generated using CCS and then the obtained ‘C’ code was loaded into the processor TMS320F2812.

3.11.1 eZdspF2812: The ezDSPF2812 is a stand alone card which provides an excellent platform to develop and run software for the TMS320F2812 processor [26]. TMS320F2812 is a TI's (Texas Instrument) product which is used to process digital data in real time. The main features of ezDSPF2812 are:

- TMS320F2812 Digital Signal Processor
- 150 MIPS operating speed
- 18K words on-chip RAM
- 128K words on-chip Flash memory
- 64K words off-chip SRAM memory
- 30 MHz clock
- 2 Expansion Connectors (Analog, I/O)
- Power supply at 5V.

The eZdspF2812 consists of four major blocks of logic:

- Analog interface connector.
- I/O interface connector.
- JTAG interface.
- Parallel port JTAG controller interface.

The architecture is shown in fig. 3.11(a).

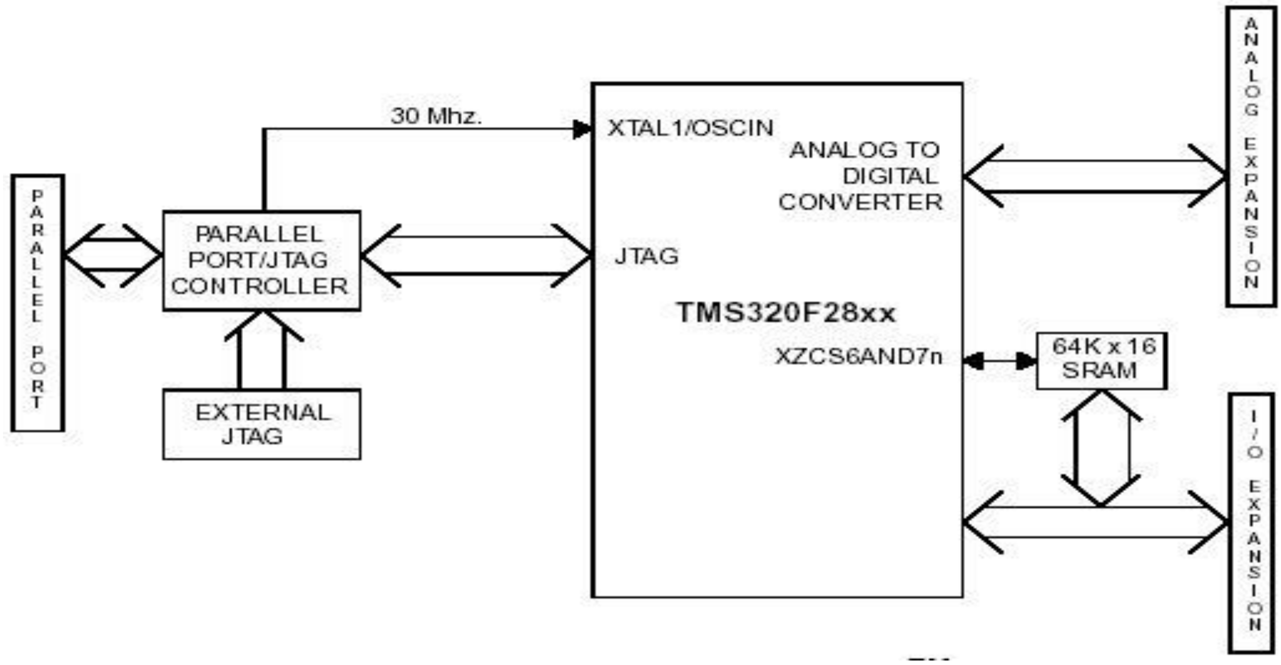


Figure 3.11(a): Block Diagram of eZdspF2812

3.11.2 CAN Module of TMS320F2812 DSP:- TMS320F2812 is a DSP which has a CAN module within it. Hence, this processor could be used as a CAN controller. Features of the CAN module of this DSP are [27]:

- Fully compliant with CAN protocol, version 2.0B.
- Supports data rate up to 1 Mbps.
- Thirty two mail boxes, each with following properties:
  - Configurable as receive or transmit.
  - Configurable with standard or extended identifier.
  - Programmable receive mask.
  - Supports Data and Remote frame.
  - Composed of 0 to 8 bytes of data.
  - Uses 32 bit time stamp on messages.
  - Programmable interrupt scheme.
  - Programmable alarm time-out.
- Low power mode.
- Programmable wake up on bus activity.
- Automatic reply to a remote request message.
- Automatic retransmission of a frame in case of loss of arbitration or error.
- Self test mode: operates in a loop back mode receiving its own message. A dummy acknowledge is provided, hence there is no need for another node to provide the acknowledge bit.

The DSP CAN controller is a full CAN controller. It contains a message handler for transmission, a reception management and frame storage. It supports data or remote frames with both standard identifier (11 bit) and extended identifier (29 bit).

When this DSP is used as a CAN node and connected to CAN bus a transceiver is needed between the DSP and CAN bus. SN65HVD230, a 3.3V CAN transceiver is used when TMS320F2812 is used for CAN applications. Fig. 3.11(b) show the CAN module of a TMS320F2812 DSP.

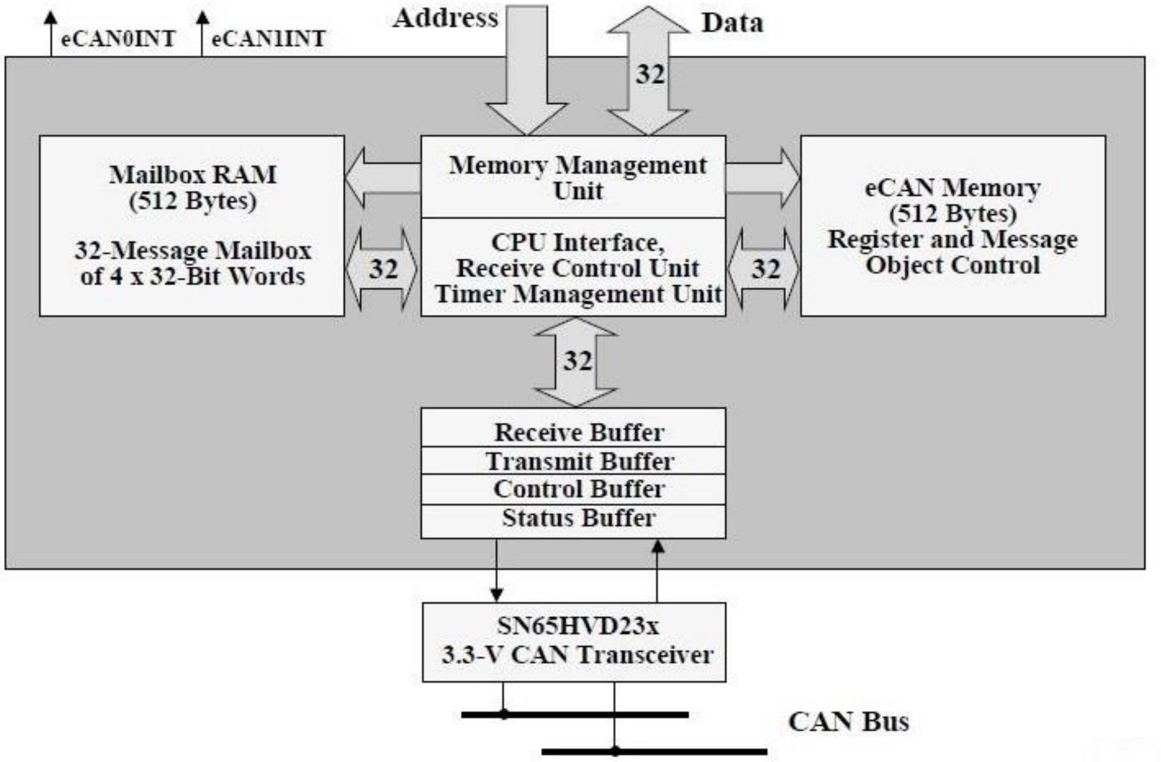


Figure 3.11(b): CAN Module of TMS320f2812

3.11.3 Loop Back Test:- The Simulink model for a loopback test with the Code Composer Studio is shown in fig. 3.11(c).

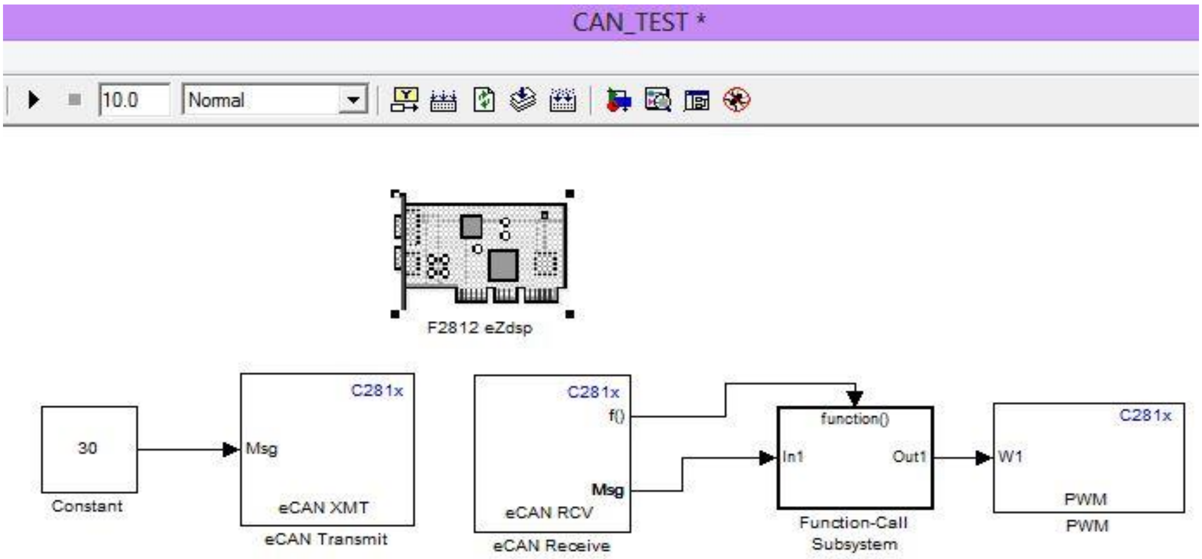


Figure 3.11(c): Simulink Model for Loopback Test

Figures 3.11(d)-3.11(f) represent the parameters configuration of various blocks used in simulation.

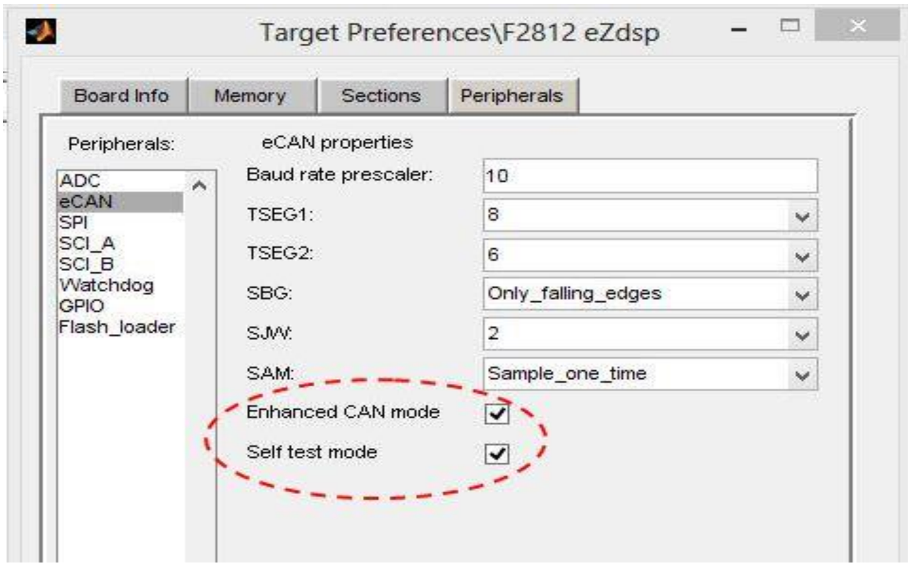


Figure 3.11(d): Parameters Configuration of F2812 Block

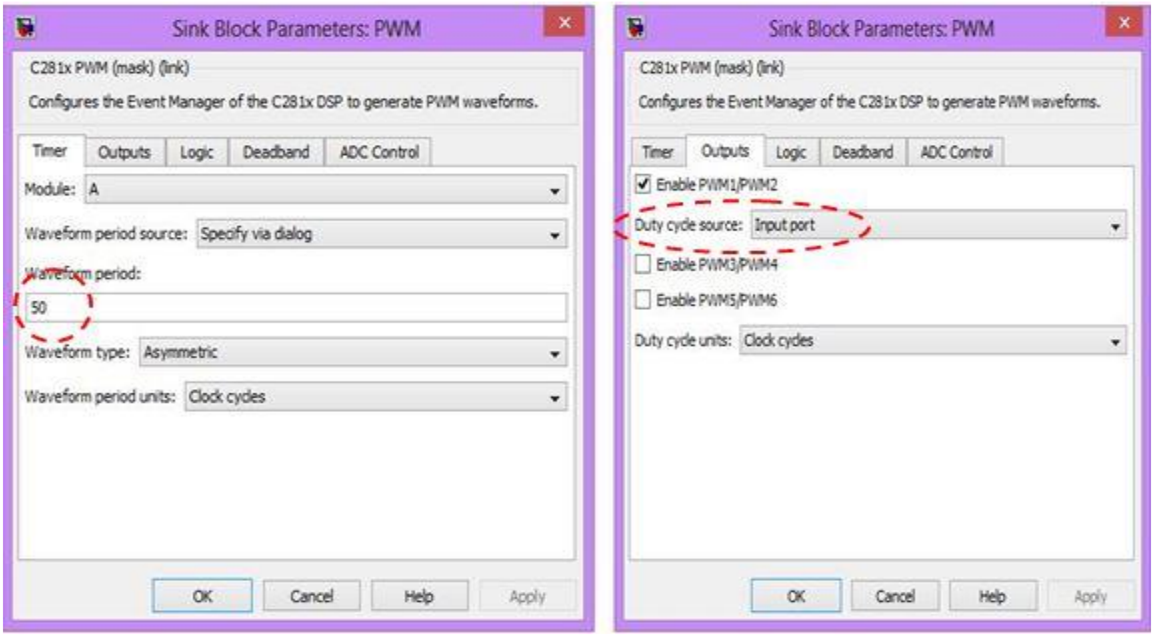


Figure 3.11(e): Parameters Configuration of PWM Block

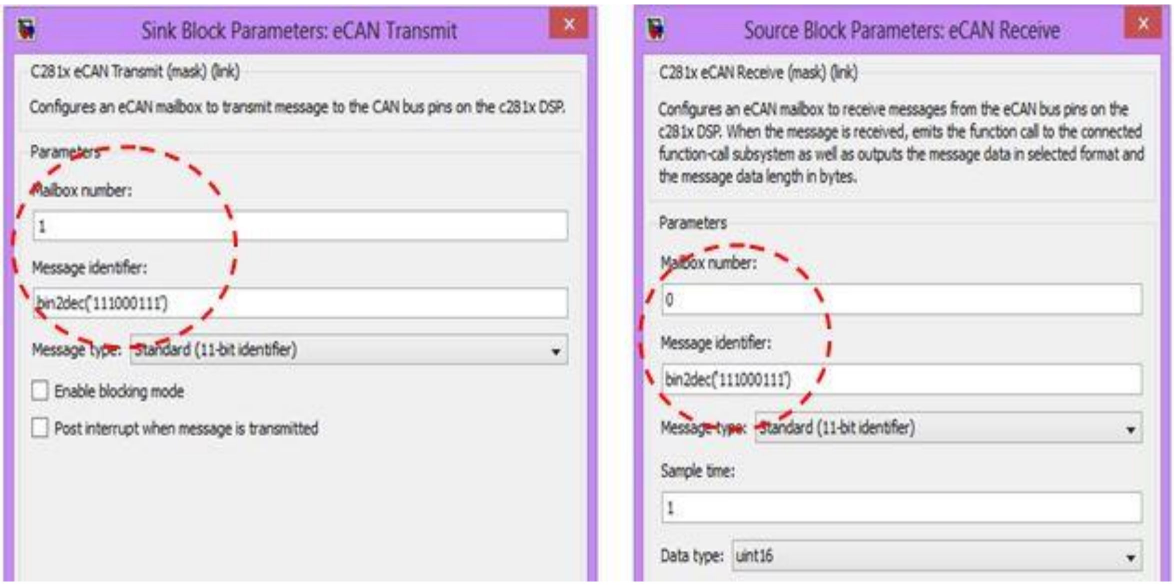


Figure 3.11(f): CAN transmit and Receive Blocks' Parameters Setting

Figure 3.11(g) is the output obtained from TMS320F2812 which is a pulse generated in PWM scheme.

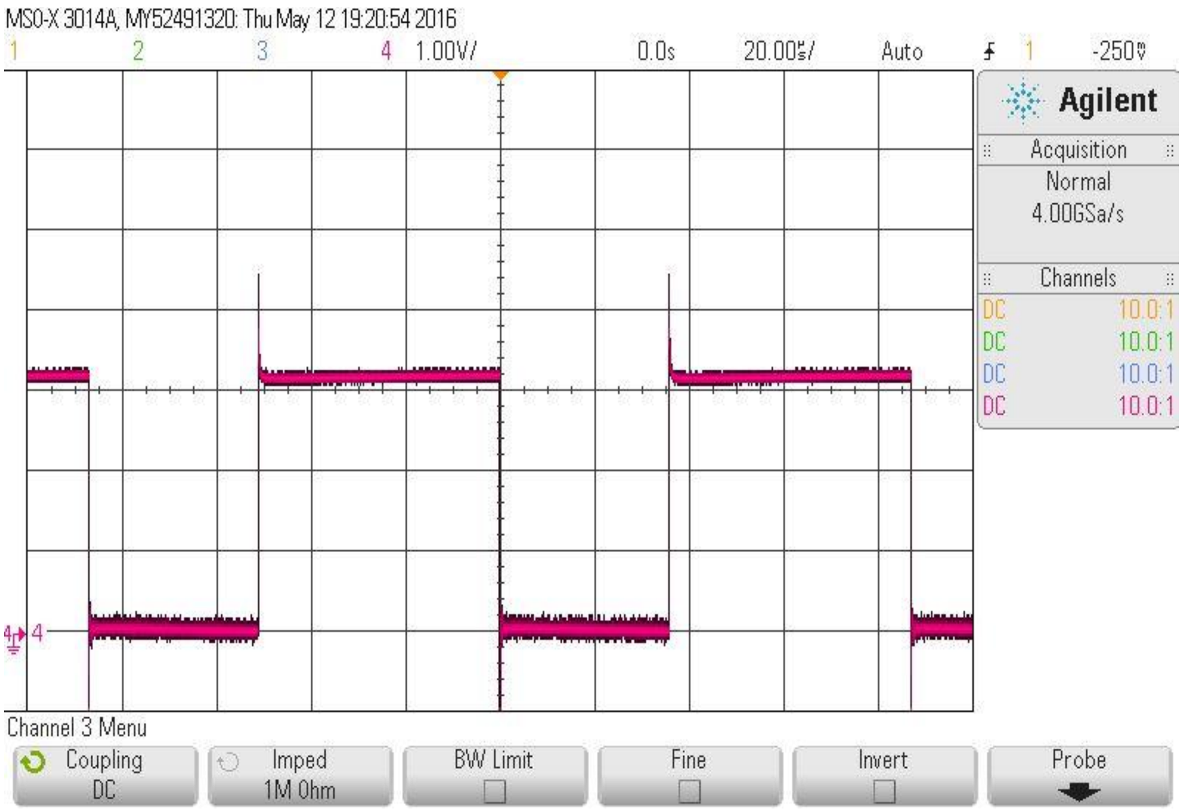


Figure 3.11(g): Output from TMS320F2812

As can be seen from the fig. 3.11(c)-3.11(g), for loop back test, it is menadatory to check ‘self-test mode’ field of ‘F2812’ bolck, the identifier of transmitter and receiver must have same identifier but they must use different mail boxes, waveform period of PWM block must be set to a finite value in previous and the duty cycle of the pulse, generated by PWM is determined by the output of the eCAN receiver (input to PWM). In order to relalize whether the receiver is capable to receive the transmitted data correctly or not, the output of receiver is seen in a PWM. Waveform period of PWM is set to 50 cycles where as the transmitted data is a contant 30. So, if the communication is proper then PWM must generate a pulse with duty cycle (30/50) = 0.6 . Figure 3.11(g) shows a pulse with duty cyle of 0.6. Hence it can be said that CAN communication in loop back mode is successful.

Chapter 4

Result and Discussion

In any four wheeled vehicle 'differential system' plays an important role. The function of differential system is to provide different amount of power to different traction wheels in order to make them rotate at different speed. This scheme is of even greater importance when the vehicle moves along a curvature. In conventional Internal Combustion engine (IC engine) vehicle, mechanical differential is used, which is an arrangement of various type of gears. In modern day's electric vehicles, mechanical differential is replaced with more efficient electronic differential (ED). The main purpose of ED is to generate speed references for each driving wheel. Steering angle (θ), given by the driver and vehicle ground speed (V) are the inputs to the ED. Steering angle θ denotes the angle at which the driver intends to change the direction of the vehicle. The ground speed (V) i.e. the linear velocity of the vehicle depends upon the command input given by the driver through accelerator pedal or brake pedal.

In this project work an ED has been proposed for 4WD4WS vehicle as described in 'section 2.3', which is capable to calculate the steering angles and reference angular velocities for each of four driving wheels. The proposed differential system is first investigated in MATLAB then it is implemented in a real time digital signal processor (TMS320F2812).

4.1 MATLAB Based Simulation:

The simulink model of an electronic differential has been designed in MATLAB, based on the mathematical model described in 'Section 2.3'. When a vehicle moves along a straight path all the four wheels have the same speed. But when the driver steers the vehicle, the ED generates different speed references for the four wheels. This proposed ED also generates the steering angle references for the wheels.

The physical parameters of a vehicle for which the ED has been designed are listed below in Table 4.1.

Table 4.1: Physical Parameters of the Vehicle

Vehicle Length (2L)	2.6 meter
Wheel Base (2W)	1.5 meter
Wheel Radius (r_w)	0.3 meter

The input parameter variations need to be presented and this is shown in the following figures. Steering angle θ and Vehicle ground speed (V) profiles as a function of time, are given in fig. 4.1 (a) and 4.1 (b) respectively.

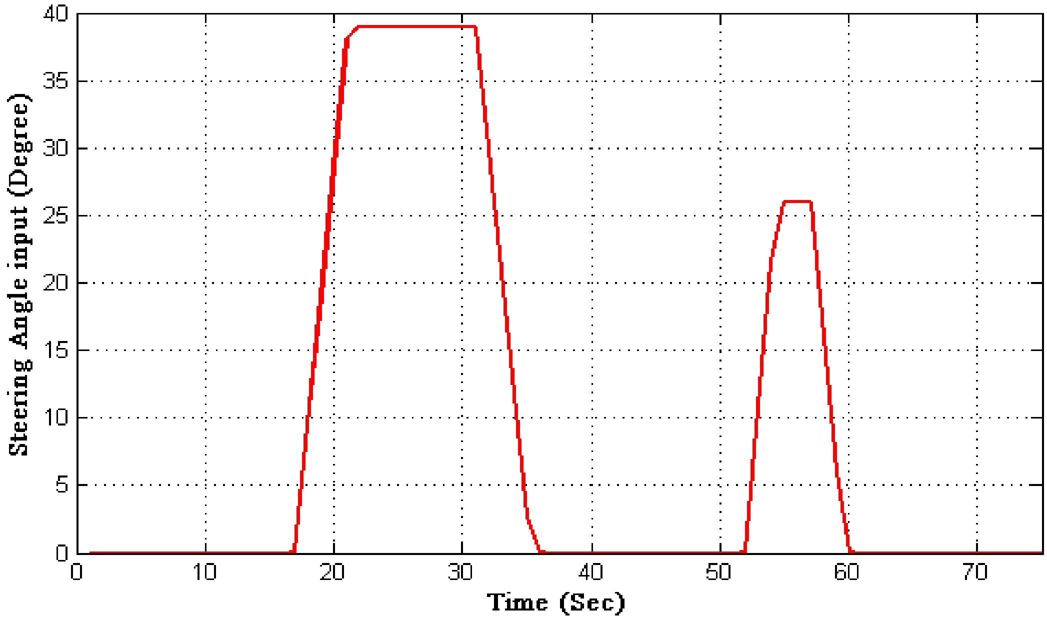


Figure 4.1(a) Steering angle input for vehicle

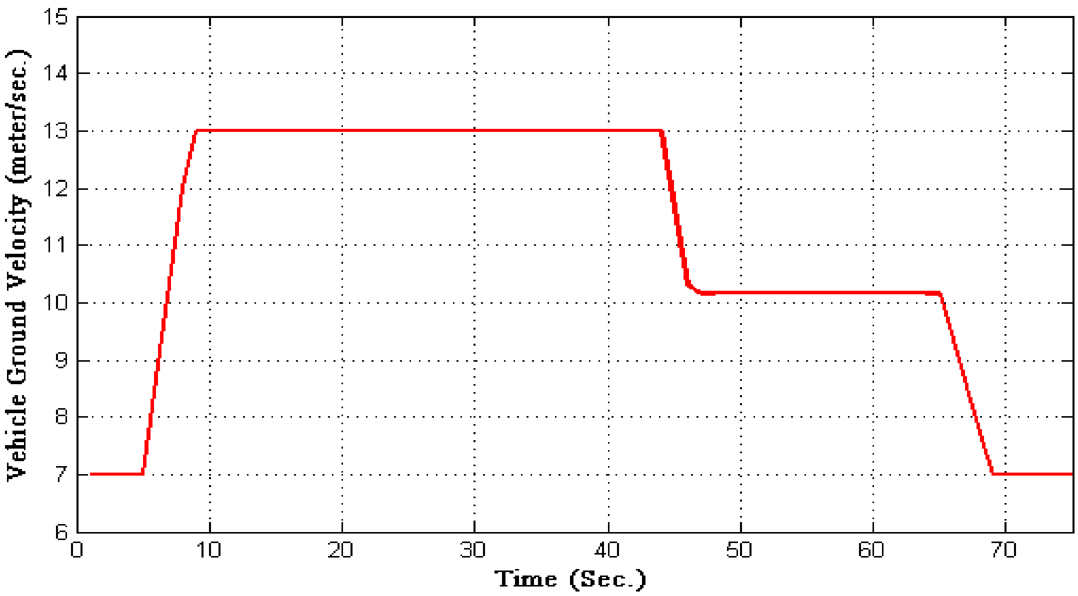


Figure 4.1 (b): Vehicle Ground Velocity

Fig. 4.1 (a) suggests that the driver steers the vehicle from about 18sec to about 36 sec and provides a maximum steering angle of 38 degrees during the entire steering process. Later, another steering operation is performed within about 52 seconds to 60 seconds. This time the steering angle reaches a maximum of 26 degrees. It can be noted that after the maximum steering angle is reached, the steering angle then falls continosusly, suggesting that a curved trajectory needs an increase in steering angle followed by a continous decrese. Figure 4.1(b) shows the reference ground velocity profile $(\mathrm{V\,vs}\ t)$ as set by the driver through accelarator or brake pedal during the vehicle's motion.

In the fig. 4.1(c) steering angle of the vehicle and ED generated steering angle references for the four wheels have been shown. Form the above figure, it can be concluded that when the vehicle follows a straight path (steering angle is zero), the steering angles of all the four wheels are also zero. This implies that the vehicle along with all the 4 wheels is moving along the forward direction that is directly ahead. But when the vehicle is steered, each of the four wheels starts to change their orientation. It is obvious from the figure that when vehicle is subjected to a small steering angle, the steering angles of all the wheels and vehicle are almost identical. The steering angles of the wheels and that of the vehicle become different when the steering angle provided to the vehicle is considerably large. For the later case, the steering angle for the two right wheels are equal, and that of the two left wheels are equal, but the right wheels and the left wheels differ in terms of magnitude of steering angle.

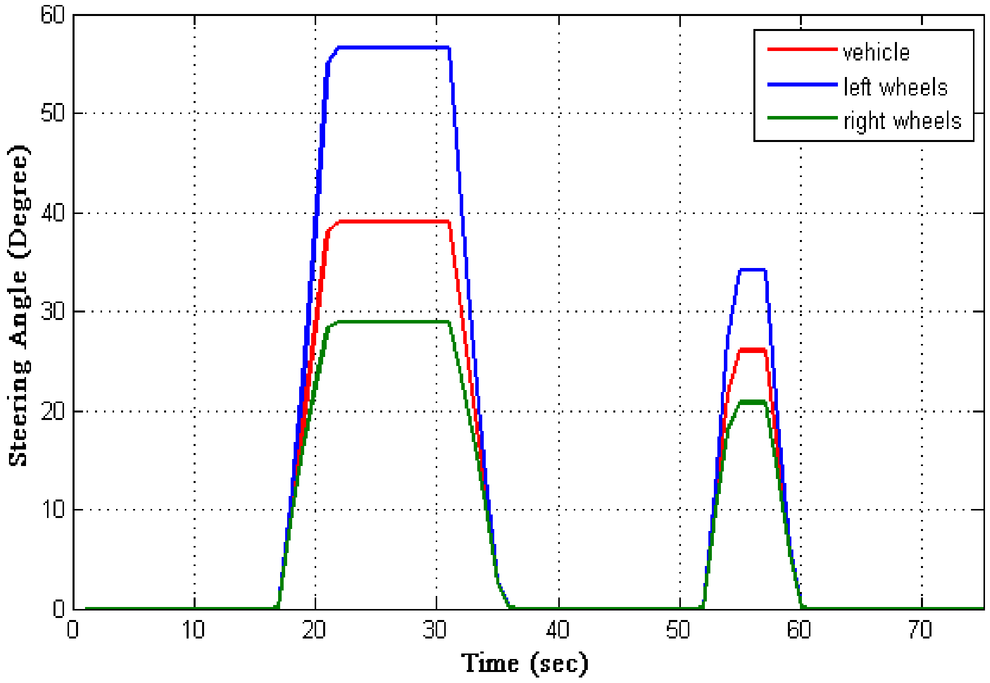


Figure 4.1(c): Steering Angles for the Vehicle and Wheels

In fig. 4.1(d) and 4.1(e) , it is seen that when the vehicle is steered, the right wheels move faster compare to the left wheels and that is why angular velocity of the right wheels is also greater compare to left wheels. When the vehicle is not steered i.e. moving straight forward, the speeds of the four wheels and the vehicle's speed are identical.

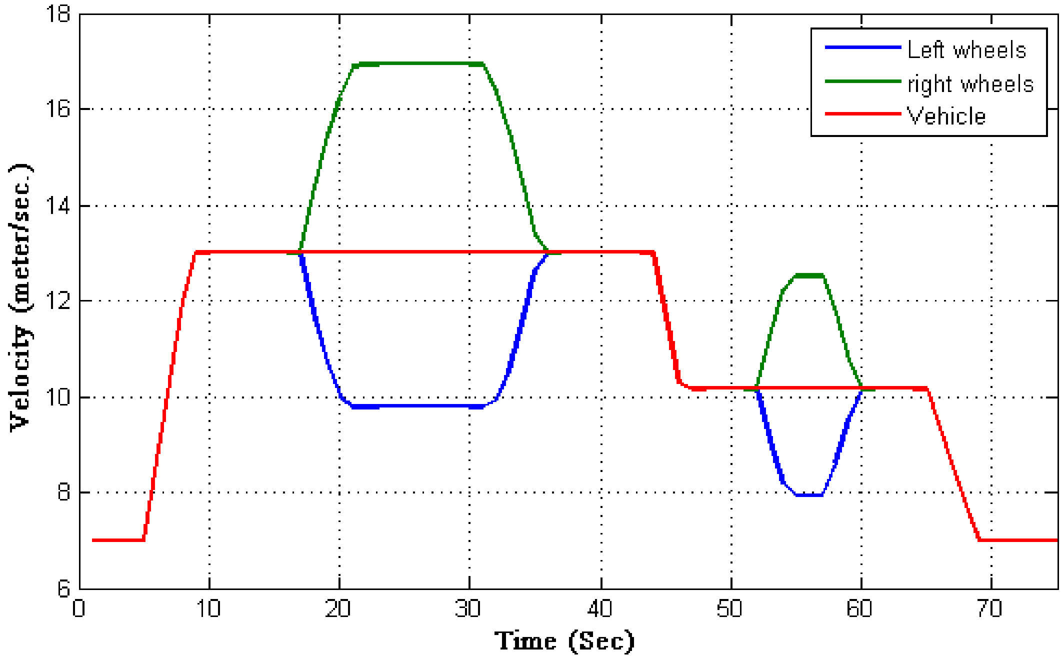


Figure 4.1(d): Linear Velocities of Different Wheels and Vehicle.

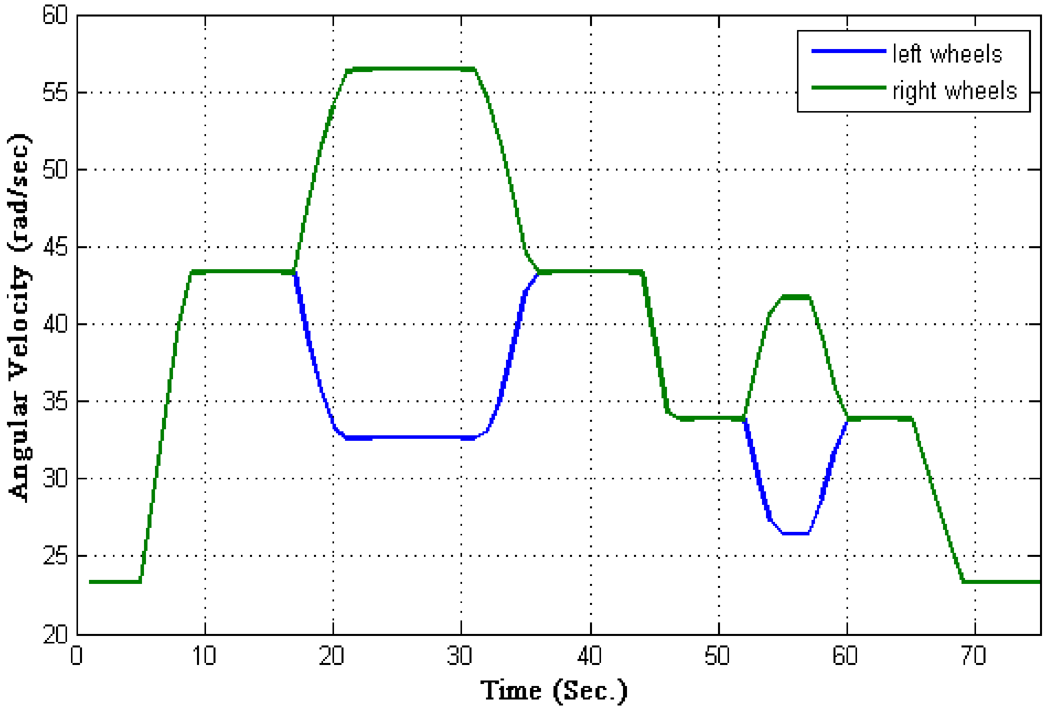


Figure 4.1(e): Angular Velocities of Four Wheels

4.2 CAN Based Design of ED:

DSP TMS320F2812 has been used to implement CAN communication system for the designing of electronic differential. TMS320F2812 is a digital signal processor which can serve the purpose of a CAN controller. The CAN module of this processor offers 32 mail boxes which can be configured as both transmitter and receiver. Hence loop back method (network contains only one node) is sufficient to design the ED and check its performance.

In the previous section, during MALAB simulation the inputs θ and V were continuous in nature but TMS320F2812 does not support continuous data for CAN communication. Besides, the fact that the DSP kit cannot provide any analog output poses a challenge for observing and tracking the simulation process because in this case bits stream are generated which are difficult to analyse.

Thus, when this DSP kit is used, the inputs θ and V have been set to some constant values and in order to realise whether the designed CAN communication scheme is operating effectively, the generated pulses are examined through Pulse Width Modulation (PWM) techniques. Therefore, the outputs (reference speed and steering angle of each wheel) of the ED are fed to PWM as inputs. The corresponding simulink model is shown in fig. 4.2(a).

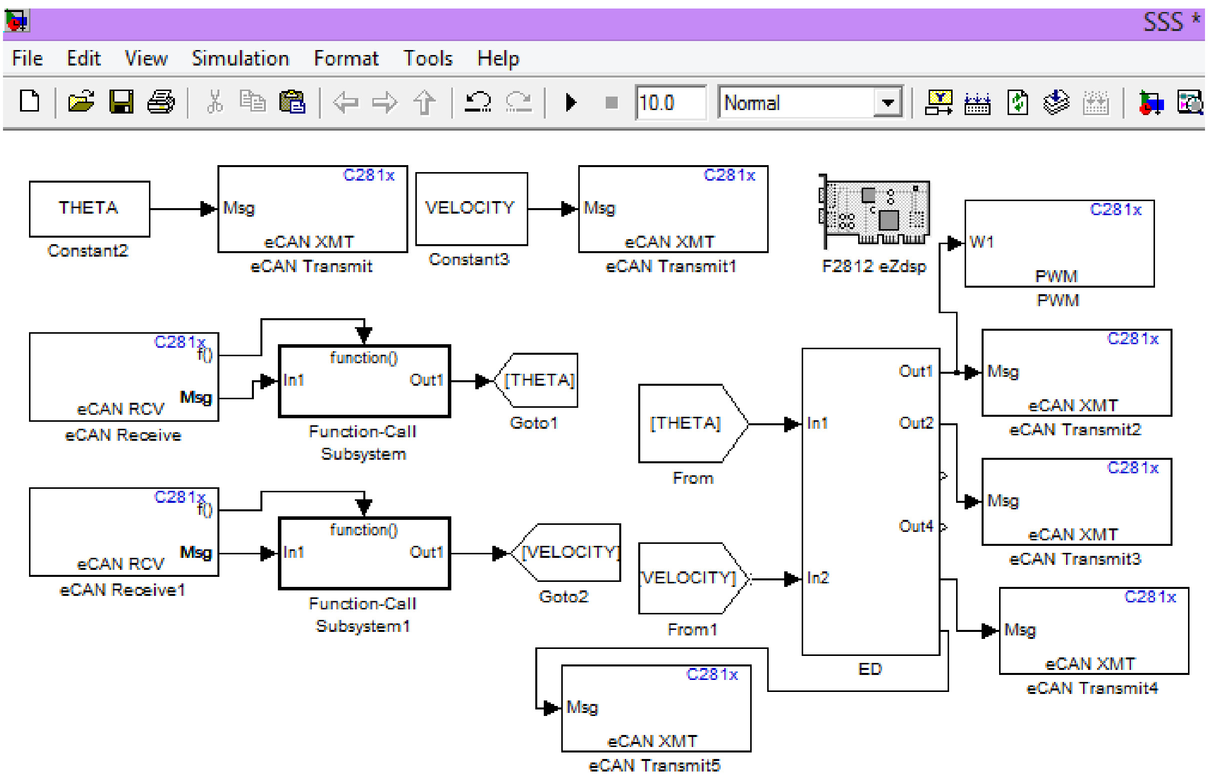


Figure 4.2(a): Simulink Model for ED with CAN Communication System

The specific values of θ and V which are used for the simulation are given in Table 4.2.

Table 4.2: Steering Angle and Reference Velocity of Vehicle

Ground Velocity of Vehicle (V)	**Steering angle input (θ)**
10 m/sec	20°

These values of V and θ are now transmitted to the ED using CAN communication. The response from the ED, obtained from both MATLAB and TMS320F2812 have been studied independently and they are compared in order to confirm whether the CAN communication system operates effectively.

4.2.1 Speed References for Left and Right Wheels:

Reference angular velocities of the wheels are shown in fig. 4.2(b) obtained from MATLAB simulation. From the fig., it can be seen that reference speed for the two left wheels is 27 rad/sec where as for the right wheels; the speed is 39 rad/sec.

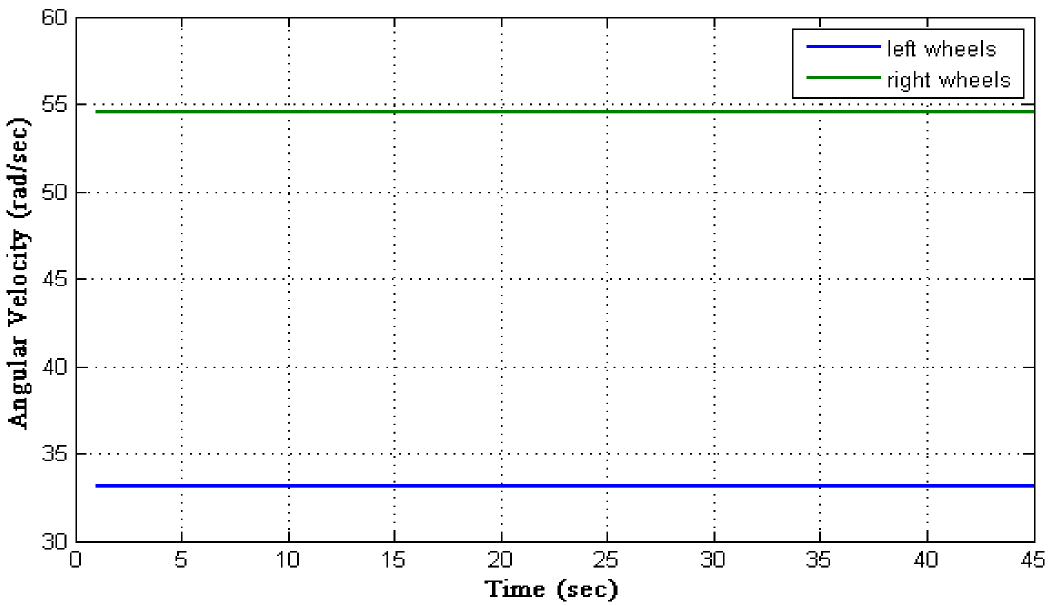


Figure 4.2(b): Different wheel's speed obtained from MATLAB simulation.

When the DSP TMS320F2812 is used, this reference speeds are fed to the input of a PWM block (as shown in fig. 4.2(a)). The waveform period of this PWM has been set to 55cycles. Thus, effective operation of the CAN communication system would mean that for the left wheels, a pulse with duty cycle (27/55) = 0.49 and for the right wheels, a pulse with duty cycle (39/55) = 0.71 is obtained. Figure 4.2 (c) which is obtained from TMS320F2812 shows that pulses with duty cycle 0.49 and 0.71 are obtained for the left and right wheels respectively. Therefore it can be concluded that CAN communication system in loopback scheme is working effectively.

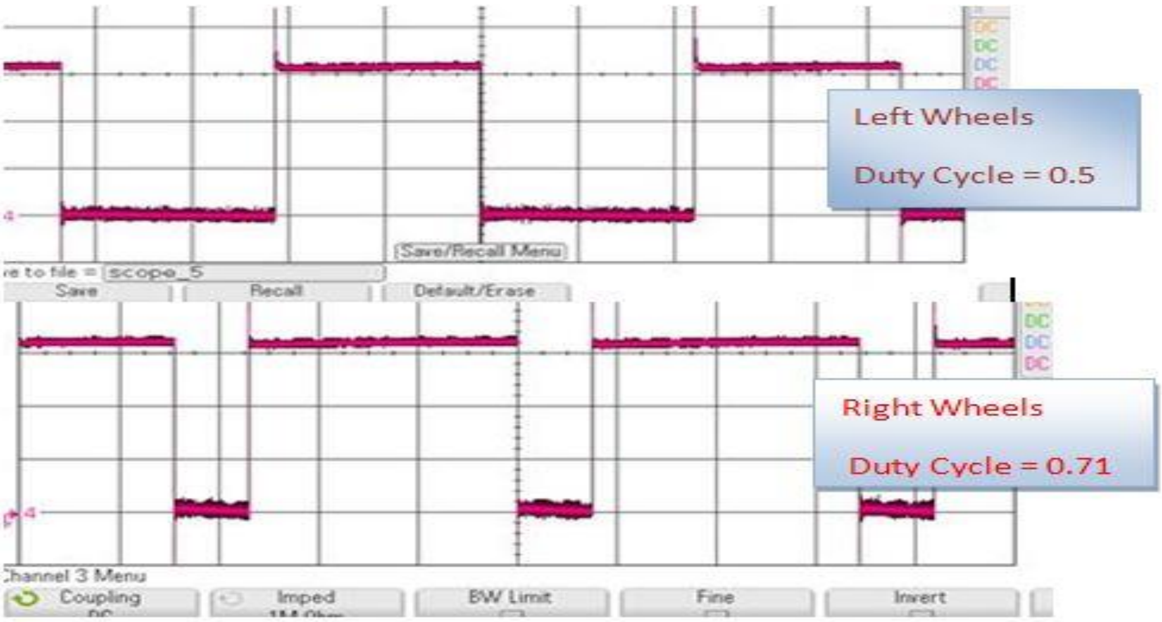


Figure 4.2(c): Output of TMS320F2812 for Different Wheel's Speed

4.2.2 Steering Angle References for Left and Right Wheels:

It is observed from the fig. 4.2(d) that when vehicle steering angle (θ) is 20° , then left wheels are steered at 25° and right wheels are at 17°.

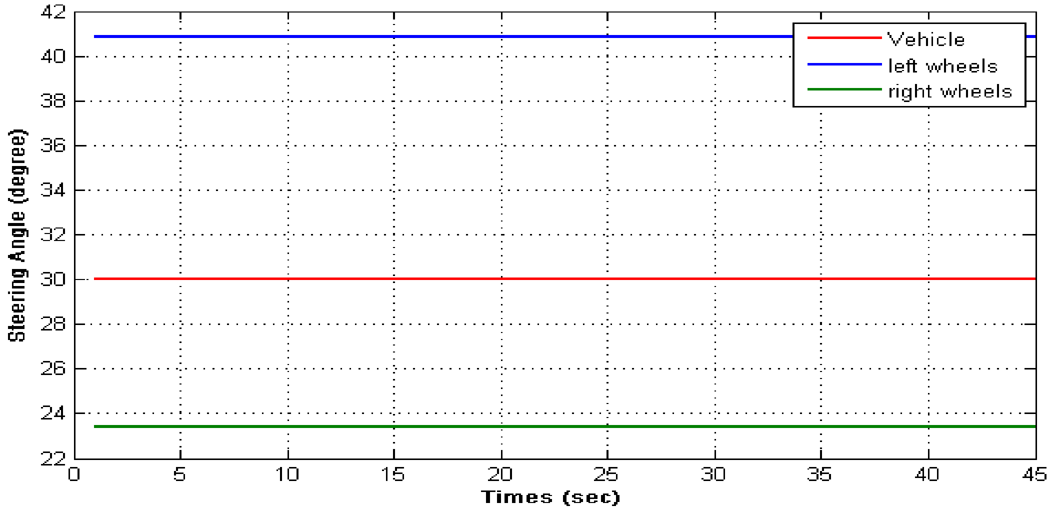


Figure 4.2 (d): Result of MATLAB Simulation for Steering Angle of Different Wheels.

For the purpose of analysing the waveforms, DSP is used and in this case the waveform period has been set to 50 cycles. Thus, effective operation of the CAN communication system would mean that for the left wheels, a pulse with duty cycle (25/50) = 0.50 and for the right wheels, a pulse with duty cycle (17/50) = 0.34 is obtained. From the fig. 4.2(e) which is the output obtained from the DSP kit can be seen that for the right wheels, the duty cycle is 0.34 and for the left wheels, the duty cycle obtained is 0.5 Thus proper functioning of the CAN communication based electronic differential is validated.

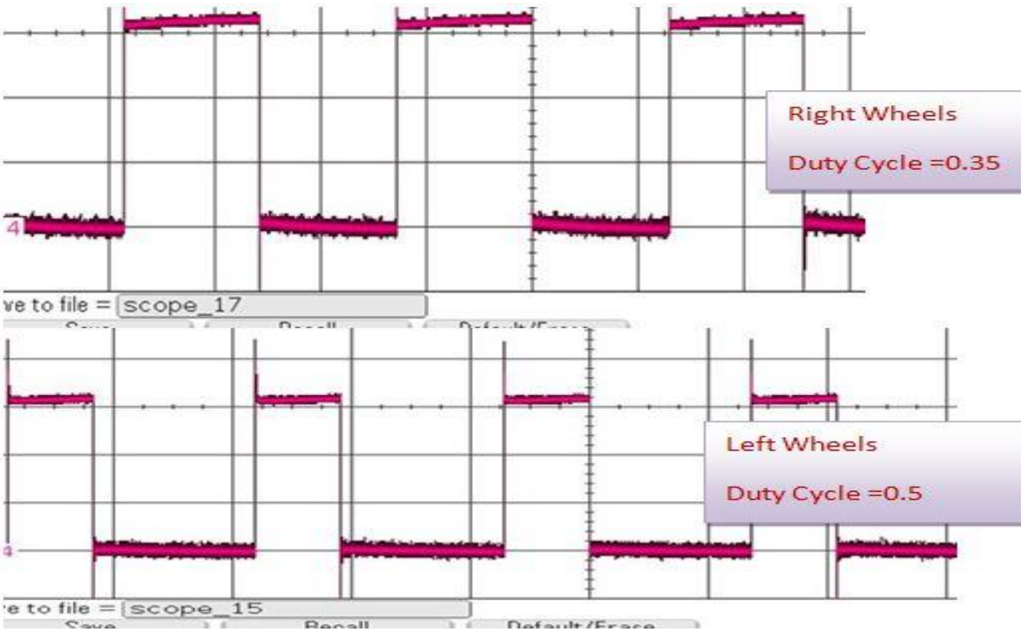


Figure 4.2(e): Output of TMS320F2812 for Steering Angle of Different Wheels.

Chapter 5

Conclusion and Future Scope of Work

5.1 Conclusion:

In this dissertation, an Electronic Differential (ED) has been designed for a Four Wheel Drive and Four Wheel Steering (4WD4WS) electric vehicle. The performance of the designed ED has been validated through both offline and online simulation, where offline simulation indicates MATLAB/SIMULINK based simulation and online simulation implies real time DSP based simulation. The DSP kit implemented here is TMS320F2812 which also introduces CAN based network communication system for communicating the reference signal generated by the ED to the corresponding traction motors. The results obtained from both the cases are identical and are in accordance to the derived mathematical results. Henceit can be concluded that the designed ED is capable of generating the reference signal effectively and also the generated signal can be efficiently communicated to the other electronic control units through CAN network system.

5.2 Future Scope:

During the development of this dissertation, at various stages of the work, several assumptions have been made. Slip angles of the wheels have been considered to be zero, wheel slippage is neglected, and mass distribution of the vehicle has been assumed to be uniform. In practical applications, however there is presence of wheel slippage. Slip angles are also present in physical systems while the mass distribution of the vehicle is usually non-uniform while the centre of mass of the vehicle will not be at the centre of the vehicle. Therefore designing of an electric differential considering all such practical scenarios shall be very effective in physical implementation of this scheme. Moreover, this dissertation generates signals for speed outputs for each of the four wheels of 4WS4WD system. Practical implementation of this work in Electric vehicles would require efficient tracking of the reference speeds by the individual motors for each wheel. Thus if local control for each of the 4 wheels can be designed such that the wheels can track the reference speeds, it can then be integrated with this work and the result will be an efficient electric vehicle that will be capable of tracking any speed change as sensed from the steering angle deviation and the linear velocity of the vehicle.

References

[1] Yee-Pien Yang, "Design of Electric Differential System for an Electric Vehicle with Dual Wheel Motors" 47th IEEE Conference on Decision and Control Cancun, Mexico, Dec. 9-11, 2008.

[2] Seref Soylu "Electric Vehicles- Modelling and Simulations." ISBN 978-953-307-477-1, pp. 4, sept. 2011.

[3] Amin Hajihosseinlu, Shaahin Filizadeh, Garry Bistyak and Erwin Dirks, "Electronic Differential Design for a Vehicle with Four Independently Controlled In-wheel Motors". University of Manitoba, Winnipeg, Canada.

[4] V.Arvind, "Optimizing the turning radius of a vehicle using symmetric four wheel steering system" International Journal of Scientific & Engineering Research, Volume 4, Issue 12, December-2013.

[5] M Schael, P. Spichartz, M. Rehlander and C. Sourkounis "Electric Differential for Electric Vehicles Using Doubly-Fed Induction Motors" Ruhr-University Bochum, Germany.

[6] Azeddine Draou, "Electronic Differential Speed Control for Two in-wheels Motors Drive Vehicle", 4th International Conference on Power Engineering, Energy and Electrical Drives Istanbul, Turkey, 13-17 May 2013.

[7] S.-i. Sakai, H. Sado, and Y. Hori, "Motion control in an electric vehicle with four independently driven in-wheel motors," *Mechatronics, IEEE/ASME Transactions on*, vol. 4, no. 1, pp. 9–16, 1999.

[8] J. Kim and H. Kim, "Electric vehicle yaw rate control using independent in-wheel motor," in *2007 Power Conversion Conference-Nagoya*, 2007,pp. 705–710.

[9] C. Geng, L. Mostefai, M. Dena¨ı, and Y. Hori, "Direct yaw-moment control of an in-wheel-motored electric vehicle based on body slip angle fuzzy observer," *Industrial Electronics, IEEE Transactions on*, vol. 56, no. 5, pp. 1411–1419, 2009.

[10] D. Kim, S. Hwang, and H. Kim, "Vehicle stability enhancement of four wheel-drive hybrid electric vehicle using rear motor control," *Vehicular Technology, IEEE Transactions on*, vol. 57, no. 2, pp. 727–735, 2008.

[11] J. Kim, C. Park, S. Hwang, Y. Hori, and H. Kim, "Control algorithmfor an independent motor-drive vehicle," *Vehicular Technology, IEEETransactions on*, vol. 59, no. 7, pp. 3213–3222, 2010.

[12] Y. Hori, Y. Toyoda, and Y. Tsuruoka, “Traction control of electric vehicle: basic experimental results using the test EV, ‘UOT’,” *IEEE Trans. on Industry Applications*, vol. 34, no. 5, pp. 1131-1138, 1998.
[13] . H. Sado, S. Sakai, Y. Hori, “Road condition estimation for traction control electric vehicle,” *Proc. of the IEEE International Symposium on Industrial Electronics*, Bled, Slovenia, vol. 2, pp. 973-978, 1999.
[14] J. Faiz, M. B. B. Sharifian, A. Keyhani, A. B. Proca, , “Sensorless direct torque control of induction motors used in electric vehicle,” *IEEE Trans. Energy Conversion*, vol. 18, no. 1, Mars. 2003.
[15] J. Faiz, S.H. Hossieni, M. Ghaneei, A. Keyhani, A. B. Proca, “Direct torque control of induction motor for electric propulsion system,” *Electric Power System Research*, vol. 51, pp. 95-101, Aug. 1999.
[16] K. Jezemik, “Speed sensorless torque control of induction motor for EVs,” *Proc. IEEE Intl. Workshop on Advanced Motion Control*, 2002, pp. 236-241.
[17] Weimin Li, Guoqing Xu, Hang Tong and Yangsheng Xu , “Design of Vehicle Control Unit Based on DSP for a Parallel HEV” , Proc. IEEE International Conference on Automation and Logistics, Aug 18-21, 2007, Jinan, China.
[18] R. Potluri and A. K. Singh, “Path-Tracking Control of an Autonomous 4WS4WD Electric Vehicle Using Its Natural Feedback Loops” , IEEE transactions on control systems technology, VOL. 23, NO. 5, SEPTEMBER 2015 .

[19] Xiaodong Wu, Li Yang and Min Xu, “Speed Following Control for Differential Steering of 4WID Electric Vehicle” Shanghai Jiaotong University, Dongchuan, China.

[20] T. Gillespice, “Fundamentals of vehicle dynamics,” *Society of Automotive Engineers*, ISBN 1-56091-199-9.

[21] M. S. Reorda and M. Violante, “On-line analysis and perturbation of CAN networks,” in *Proc. 19th IEEE DFT*, Oct. 2004, pp. 424–432.

[22] L.Varghese, “Implementation of Controller Area Network for Automotive Application” Master degree thesis , NIT Rourkela(Dept. Of Electronics and Communication Engineering), 2008.

[23] E. G. Schmidt, K. Schmidt, “Message scheduling for the FlexRay protocol: the dynamic segment,” *IEEE Transactions on Vehicular Technology*, vol.58, no.5, 2009, pp.2160-2169.

[24] K. Tindell, A. Burns, A. J. Wellings, “Calculation controller area network (CAN) message response times,” *Control Engineering Practice,* vol.3, no.8, 2000, pp.1163-1169.

[25] https://en.wikipedia.org/wiki/CAN_bus.

[26] “eZdspF2812 tutorial”, available at www.ti.com.

[27] “TMS320F2812 Digital Signal Processor Implementation Tutorial”, available at www.ti.com.