Design and Development of Advanced Steering System for Low Speed Applications

Submitted in partial fulfilment of the requirements

of the degree of

Bachelor of Technology

By

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Project carried out at

School of Mechanical Engineering

Vellore Institute of Technology

2019

CERTIFICATE

This is to certify that the dissertation work titled **Design and Development of Advanced Steering System for Low Speed Applications** is submitted by **Saksham Verma, Shreyas Shanker** and **Govind Ajith Kumar** bearing registration Numbers **15BMA0008, 15BMA0009** and **15BMA0013** to the School of Mechanical Engineering of the VIT University, Vellore and ARAI Academy, The Automotive Research Association of India, Pune, in partial fulfilment of the requirements for the degree of Bachelor of Technology in Automotive Engineering. This is a bonafide work carried out at **ARAI-FID** by him under our supervision. The contents of this dissertation, in full or in parts have not been submitted to any other institute or university for the award of any degree.

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Internal Examiner

External Examiner

Date: 31st May, 2019

DECLARATION

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which thus not have been properly cited or from whom proper permission has not been taken when needed.

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Date: 31st May, 2019

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This project is a culmination of our efforts over the last 6 months. However, the knowledge gained and the concepts applied have been a product of constant work by our faculties, mentors and undoubtedly the impeccable facilities provided by Vellore Institute of Technology, Vellore and Automotive Research Association of India – FID.

We would like to thank Dr G. Viswanathan, Chancellor, VIT for the opportunity to study the science of Automotive Engineering at two prestigious institutions during our Bachelors Degree. We would also like to extend our gratitude towards our guide, Dr Sanjay Patil. His constant inputs to the project kept us working hard to meet his level of expectations and kept us motivated throughout the duration of this project. We would also like to thank Prof. Ashok B and Prof. C. D. Naiju who has been a constant help for us during the course of this project. Finally, we extend our gratitude towards Dr Thundil Karuppa Raj, Head of Automotive Engineering Department and Dr K. C. Vora, Senior Deputy Director and Head of ARAI Academy, ARAI India and all other faculties at VIT Vellore and ARAI-FID for sharing guiding us through this period and sharing their vast knowledge bank with us.

Lastly, we would like to take this opportunity to extend our profound gratitude towards our friends, family and almighty for the blessings and encouragement without which this project would not be possible.

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ABSTRACT

The vehicle steering system is an essential part of the vehicle dynamics of the automobile. While conventional steering system can perfectly perform the work of guiding the vehicle along straight line or curved paths, it is ridden with inherent flaws. These flaws include increased turning circle radius, reduction in high speed turning stability and the inability to negotiate a zero turn steer. Even the under-steer and over-steer characteristics do not help advocate conventional steering systems.

The work proposed in this project, deals with the packaging of crab steer, four-wheel steer and zero-turn steer into one comprehensive steering system package, with the use of electric motors. Four wheel steer turns the rear wheels in the counter phase direction to the front wheels and aids in reducing low speed turning circles. Zero steer enables the vehicle to turn about its vertical axis so that, the vehicle can be manoeuvred at dead-ends and tight spaces with minimal effort. The entire prototype is built with a combination of mechanical, electrical and hydraulic systems. For ease of use and pragmatic purposes, the prototype can be controlled using a remote module, also custom built for the needs of this project.

The prototype built was tested to observe the reduction in turning circle radius when switched between two wheel steer and four wheel steer. A minimum reduction percentage of TCR as 49.1% and a maximum reduction percentage of 63.83% were observed after testing the prototype. Further, zero steer was tested and the vehicle was seen to have a turning circle radius of virtually zero. Having verified the testing results, a CAD model was made for a potential design of an electric wheel chair, thereby implementing the idea in real world applications. The wheel chair designed has four servo motors on each corner to aid with direction and hub motors for vehicle propulsion. Further stress analysis was conducted on the said wheelchair using ANSYS 16.2 Workbench. A factor of safety above 2 was noticed. This validates the design.

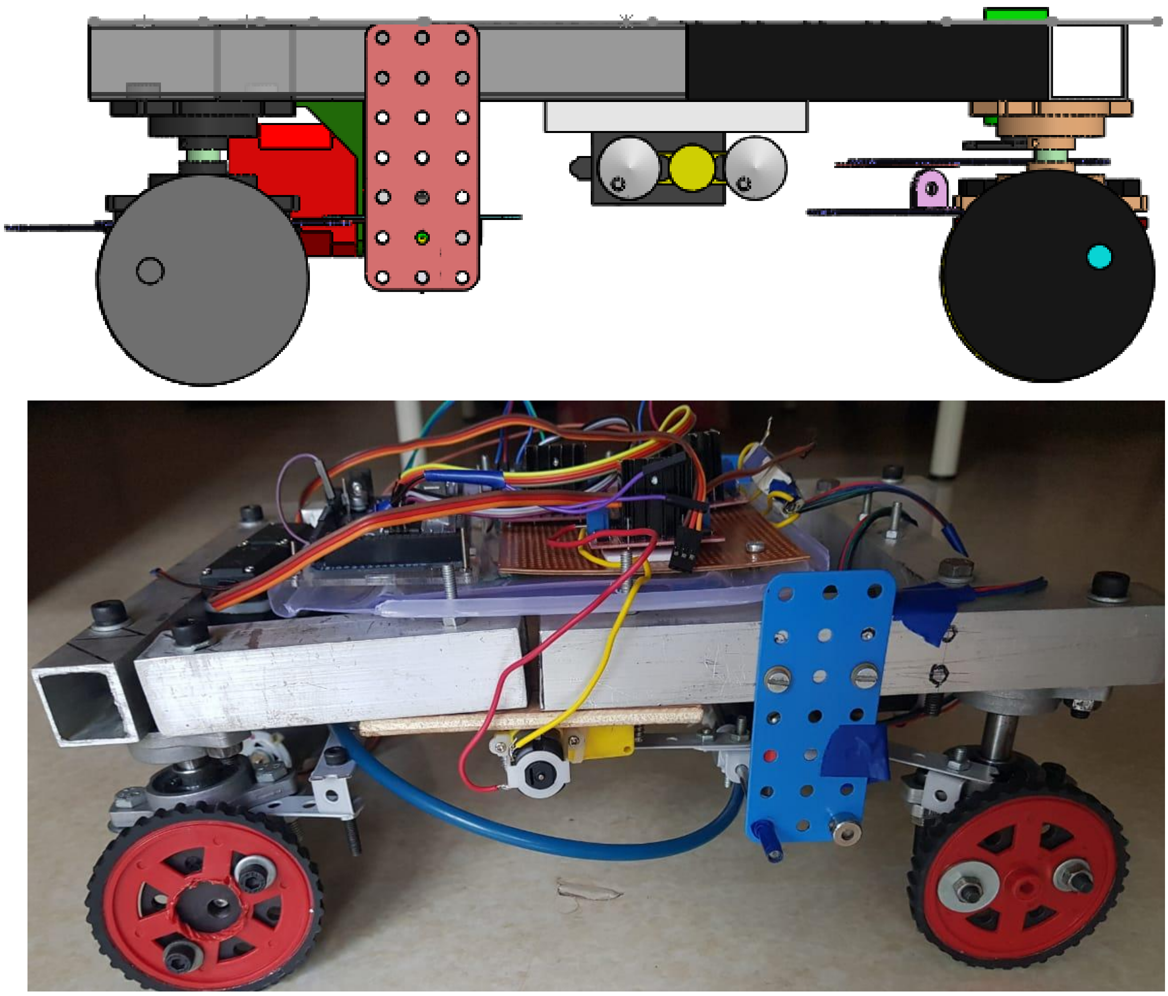
This design is iterative and can be tailored to specific applications in various industries. The work proposed in this project can find its use in a wide breadth of domains. Some of these applications include agriculture (tractors, farm equipments), warehouses, heavy industries, medical industries (wheelchairs), all terrain vehicles and off-roaders. With iterations, the steering system can be tailored to very specific low-speed and high-speed applications.

Keywords: Zero Turn Steer, Four Wheel Steer, Steering, Wheelchair

PROJECT EXECUTIVE SUMMARY

The objective of this project is to develop a comprehensive four wheel steering system package. The prototype is aimed at developing a package which can switch between various modes of four wheel steer, crab steer and zero turn steer, for a typical application of wheelchair.

While four wheel steering system has been deployed for over 20 years in the automobile industry, its application by combination with zero-turn steer has been few. This provides an opportunity to venture into this space to explore the opportunities to implement such a system for a wheel chair.



Final Prototype Build (Top: CAD MODEL, Bottom: Actual build)

This project has gone through stages of development of a prototype that portrays the idea of an advanced steering system, specially tailored for low speed applications. The build of the vehicle lasted a period of six months, including testing and result analysis. The project is a culmination of mechanical, electrical, electronic and hydraulic principles which when brought together provides a prototype fully capable of demonstrating various steering manoeuvres such as counter-phase steering, conventional steering and zero turn steering mechanism.

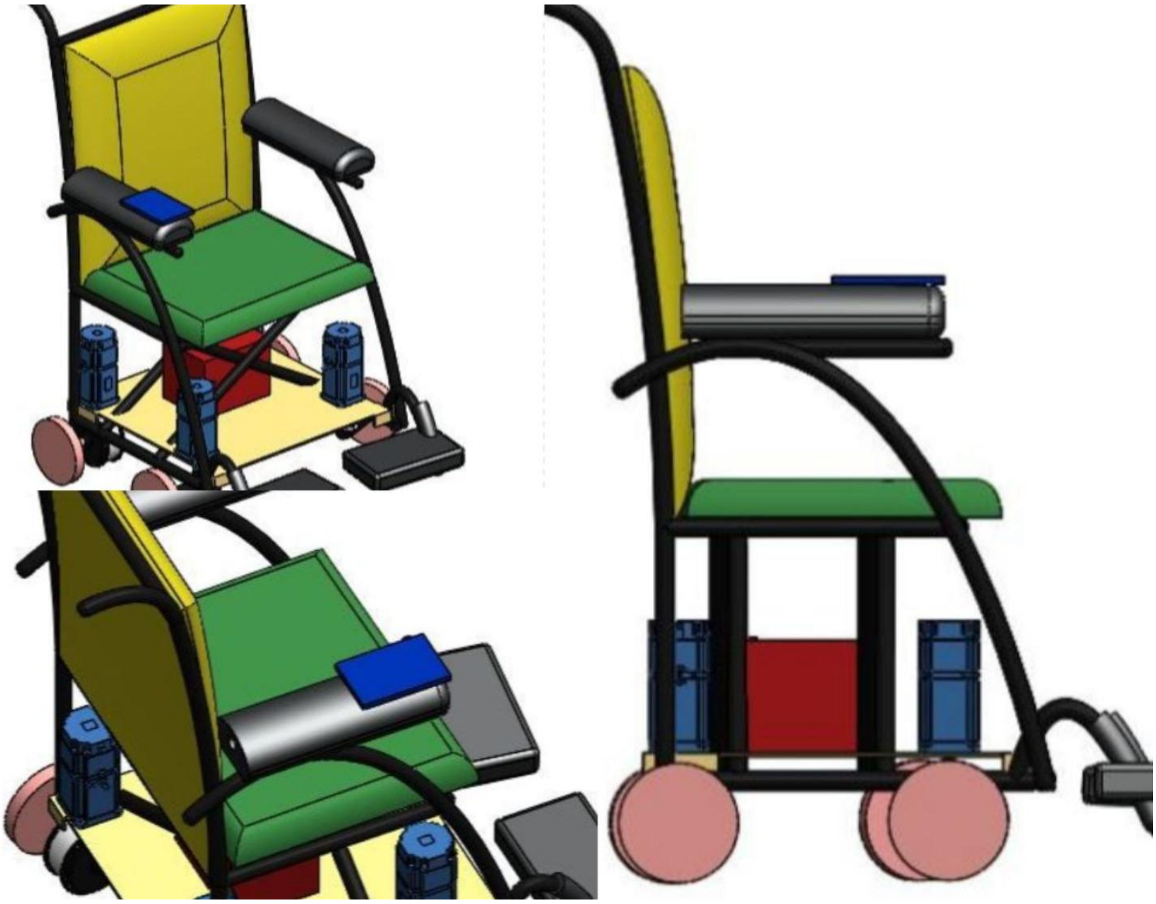
This system is controlled by two Arduino Unos mounted on the vehicle and three motor drivers. The motor drivers are used to drive the DC motors (for vehicle propulsion), for stepper motor (for turning the front wheel rack) and for the secondary DC motor (to attain zero turn steer) [1].

These motors further work in tandem with the servo motors that is used to turn the rear wheel via a four bar mechanism. The Arduino unos are coded using the Arduino IDE Software. To check the values with the literature, a comprehensive MATLAB code was developed that can output the values with regards to the dimensions of the vehicle.

The measured values were plotted and a trend line was obtained. A third degree polynomial with a good fit is used to represent the proposed steering mechanism. This polynomial helps interpolate the values in between which further helps understand the reduction in turning circle radius throughout the range. It is seen that the Coefficient of Determination (R^2) is close to one which depicts the closeness of fit of the trend line to the plotted values.

The values were tabulated and the reduction in TCR between two wheel steering and four wheel steering were obtained and tabulated as well. A minimum reduction percentage of TCR as 49.1% and a maximum reduction percentage of 63.83% against an aim of 20% set as target during the initial stages.

This indicates that the proposed build has been successful in integrating 2WS (conventional steering system), 4WS (counter phase steering) and zero turn steering systems in a comprehensive electro-mechanical system combined with hydraulic systems as one robust package.



Prototype of A Wheelchair Build to Demonstrate Possible Applications of The Developed Steering System

Additionally, a model of an electric wheel chair was developed. This electric model portrays an example of the implementation of the idea and can be developed based on the prototype developed for this project. While substantial changes have to be made, the gist of the technology remains the same and can find its used in a wide variety of industries. Further stress analysis was performed on the wheelchair using ANSYS 16.2 workbench. This simulation provided a factor of safety of above 2, thereby proving safe for regular usage.

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ABBREVIATIONS

2WS	Two Wheel Steering
4WS	Four Wheel Steering
ATV	All Terrain Vehicle
CAD	Computer Aided Design
DC	Direct Current
DFMEA	Design Failure Mode Analysis
FoS	Factor of Safety
IDE	Integrated Development Environment
PWM	Pulse Width Modulation
TCCD	Turning Circle Clearance diameter
YCD	Turning Circle Diameter
TCR	Turning Circle Radius
ZTS	Zero Turn Steer

Chapter 1 Introduction

The steering system of a vehicle is an essential component to impart stability to the vehicle while travelling in a straight line and around corners, both during low speed and high speed manoeuvres. While conventional steering system (2WS) can prove to be the most optimal solution, both from a complexity and an economical front, but it still has a huge room for improvement in various other real world situations. These include:

- High speed turns and lane changing,
- Low speed tight corners,
- Navigating at dead ends.

These challenges have driven research to new directions and have given a plethora of innovative solutions, including the concept of Four Wheel steering (4WS). The system was called the High Capacity Actively Controlled Steering (HICAS), was back in 1986.[2]. In this steering system, the variation in turning direction of the rear wheels with respect to the front wheels will determine the change in vehicle dynamics. Two separate concepts of in-phase steering and counter-phase steering are employed which are explained in detail in the subsequent chapters. [3]

The 4WS upon varying the turning angles of the individual wheels effectively reduces the wheelbase of the vehicle. Hence, the driver will feel like he is driving a vehicle shorter in length than it actually is, which can enable him to drive out of parking spaces with minimal effort and relative ease.

All terrain vehicles such as tractors, dune buggies and other off road vehicles find themselves negotiating tight corners and high speed manoeuvres all the time. This project aims to develop a steering system for just that, while inculcating an added mode of zero turn steer.

1.1 Project Background

In this project, the aim is to study the working of the 4WS and zero-turn steering and develop a prototype which can be comparable in dimensions to and actual wheel chair. A prototype depicting the concept of zero turn steer is built using a combination of electrical, mechanical and hydraulic build. The model is tested and the difference between the TCR of 2WS and 4WS.

Further, a CAD model of an electric wheel chair is made and simulations were conducted on MATLAB and structural analysis was carried out on ANSYS Workbench 16.0.

1.2 Needs and Objectives

The need to develop this system can be justified by the reduction in TCD provided by this system. In real world application, an array of sensors and actuators can measure the steering wheel angle and the wheel turning speed to actuate the four wheels for minimizing the TCD or maximising cornering stability, depending on the requirement. However, the prototype this project aims to work on is designed to depict that of a wheelchair, using its dimensions.

The objective is to develop this prototype and gain positive reduction in TCD of 20% or higher. The project also aims to simulate this on MATLAB and validation will be done through the physical prototype.

1.3 Targets of the Project

The target is to obtain a minimum of 20% reduction in turning radius using the 4WS Prototype. The 4WS prototype is designed to turn all four motors using its extensive deployment of electric motors, thereby increasing the wheel articulation about its pivot point at all four corners of the wheelchair.

The reduction in TCD can be measured using conventional turning circle radius (TCD) measuring methods.

1.4 Project Proposal Sheet

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Students Project Proposal for B. Tech Programme at ARAI

1.		**Project Title**	DESIGN AND DEVELOPMENT OF ADVANCED ALL-WHEEL STEERING SYSTEM FOR LOW SPEED APPLICATIONS			
2.		**Industry / Institute**	ARAI - FID			
3.		**Project Duration**	**03rd Dec 2018 to 31st May 2019**			
4.		**Project Category**				
	4.1	**Design Elements to be Included** (Inclusive of Mandatory Min 3) ***Mandatory**	X	Engineering Standard*	X	Prototype and Fabrication
			X	Design Analysis*		Experimentation
			X	Modeling and Simulation		Software Development
	4.2	**Realistic Constraint to be Addressed** (Minimum 3)	X	Economic		Ethical
				Environmental	X	Health and Safety
			X	Social		Manufacturability
				Political		Sustainability
5.		**Related Standards, Regulations, Reference Literature, if any**				
6.		**Objectives & Target of the Project**	Design of an advanced all-wheel steering system that can achieve 4-wheel steer and zero-angle steer in a single package, and demonstrate the same using a prototype for low speed applications			
7.		**Need and Justification**	All-wheel steering will give easy maneuverability and help reduce turning circle diameter. Zero-angle steer can help disabled patients, agricultural and construction vehicles thereby allowing easier parking and mobility.			
8.		**How your Department is capable of taking up this Project?**				
	a)	Existing facilities / infrastructure/Software	Design Lab (MATLAB, SolidWorks, Arduino)			
	b)	Competences/ experience				
	c)	Studies conducted / publications, if any				
9.		**Monthly Stipend**				
10.		**Remarks**				

Signature:								
	Student 1	Student 2	Student 3	VIT HOD	University Guide		ARAI Guide	ARAI Academy Head
Name	Saksham Verma	Shreyas Shanker	Govind Ajith Kumar	Prof. Dr. Thundil Karuppa Raj	C D Naiju	Ashok B	Sanjay Patil	Dr. K C Vora
Designation	Student	Student	Student	HOD	Assistant Professor (Senior)	Assistant Professor (Senior)	Deputy Director	Sr. Dy. Director & Head
Department	VIT B. Tech	VIT B. Tech	VIT B. Tech	Automotive	Automotive - VIT	Automotive - VIT	ARAI FID	ARAI Academy
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Email ID	saksham.verma 2015@vit.ac.in	shreyas.shanker 2015 @vit.ac.in	govindajith.kumar 2015@vit.ac.in	hod.ae @vit.ac.in	cdnaiju@vit.ac.in	ashok.b @vit.ac.in	sapatil.pga@araiindia.com	vora.pga@araiindia.com

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PROJECT SCHEDULE [PLAN]

Name of the Student/s : Saksham Verma, Shreyas Shanker, Govind Ajith Kumar
Registration No. : 15BMA0008/15BMA0009/15BMA0013

University, Course & Branch of Study: VIT University [B. Tech] / Mechanical Engineering (specialized in Automotive Engineering)

Name of Project Guide/s : CD NAIJU (VIT), Ashok B (VIT) & Sanjay Patil (ARAI FID)

Project Title : DESIGN AND DEVELOPMENT OF ADVANCED ALL-WHEEL STEERING SYSTEM FOR LOW SPEED APPLICATIONS

Major Activities	Target Date
Student physically report to Guide	03-12-2018
Literature Survey	03-12-2018 to 28-12-2018
Finalization of Objectives & Methodology	21-12-2018
Project Proposal, Project Schedule and Brief Description of Project	28-12-2018
M.S. Project Plan to be submitted by student	04-01-2019
First Project Review of VIT/VTU students by Guide/s (Review I)	14-01-2019 to 25-01-2019
Marks out of 50 from Reporting Guide by e-mail to Academy	31-01-2019
Report, PPT & Intermediate Review at Project Site (Review II) with Head / Faculty, ARAI Academy	18-02-2019 to 29-03-2019
Marks out of 100 jointly given by Reporting Guide, Academy Faculty/University Faculty to be declared	05-04-2019
Submission of Draft Report to Guide	06-05-2019
Submission of Modified Report to Guide	13-05-2019
Submission of Modified Report to Head, ARAI Academy	20-05-2019
Submission of Final Bound Report to Head, ARAI Academy	24-05-2019
Final Presentation & Viva –Voce with Internal / External Examiner at ARAI, Pune (Review III)	27-05-2019 to 31-05-2019
Marks out of 350 jointly given by External & Internal examiners to ARAI Academy for Viva- Voce	07-06-2019
Total Marks out of 500 given by Academy and e-mail to University	15-06-2019

Date:

Signature of the Student

Signature of the Guide/s

Signature of Head, ARAI Academy

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Objective, Brief Description, Methodology & Target of the Intended Project

Objective: To develop an adaptive 4WS system using a combination of Mechanical and Electronic systems that enhances the manoeuvrability of the vehicle by gaining a positive reduction in the turning circle radius of the vehicle.

Brief Description: Four wheel-steered vehicles have inherent advantages over conventional front-wheel steered vehicles. Some of these advantages include smaller turning radius and high speed stability. Over the years many construction and passenger vehicles have used this system for the above mentioned benefits. The aim of this project is to incorporate the zero-angle steer into a prototype to facilitate even easier maneuverability. This system can be of added advantage in low speed applications such as wheelchairs, bots, construction, farming and other commercial sectors. The prototype should allow for easy switching between multiple modes upon request.

Methodology:

1. Study relevant literature from reputed journals (SAE, ELSEVIER, etc) regarding four wheel steering.
2. To decide the steering behavior for the front and rear wheels.
3. To design the steering geometry on SolidWorks based on the steering behavior.
4. Decide Motor specifications and calculations of gear ratios.
5. Design vehicle body and mounting of steering and suspension components.
6. MATLAB simulation of steering behavior.
7. ARDUINO coding for the driving and steering motors & actuators present.
8. Assembly of the model.
9. Testing of the final prototype.
10. Calculation and comparison of turning circle radii as opposed to a conventional front wheel steered vehicle of comparable specifications.

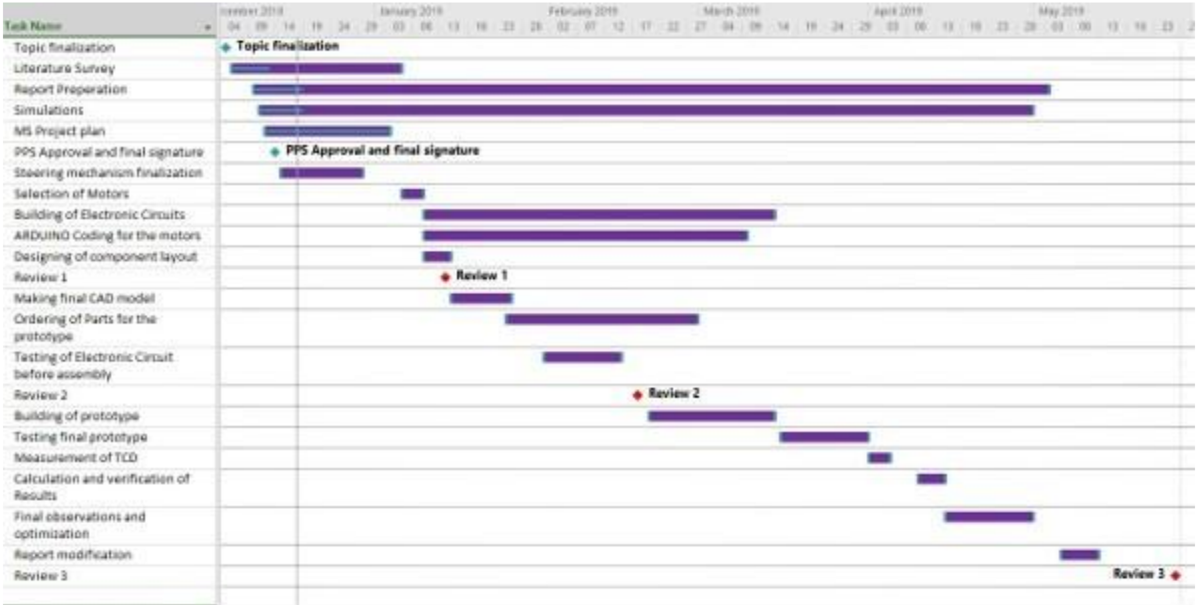
Target:
Build a robust working prototype which can demonstrate the desired all wheel steering characteristics while giving positive reduction of at least 20% turning circle radius

Date: Signature of the Student Signature-of the Guide/s

Signature of Head, ARAI Academy

1.5 MS Project Plan

Using MS Project software we created a target plan for the progression of the project from inception to completion. This allowed us to track our progress and get to our set goals within the decided time frame and conform to them.



Task Name	Start	Finish	Duration
Topic finalization	05 December 2018	05 December 2018	
Literature Survey	06 December 2018	05 January 2019	24 days
Report Preperation	10 December 2018	03 May 2019	106 days
Simulations	11 December 2018	30 April 2019	102 days
MS Project plan	12 December 2018	03 January 2019	18 days
PPS Approval and final signature	14 December 2018	14 December 2018	
Steering mechanism finalization	15 December 2018	30 December 2018	12 days
Selection of Motors	06 January 2019	10 January 2019	5 days
Building of Electronic Circuits	10 January 2019	15 March 2019	47 days
ARDUINO Coding for the motors	10 January 2019	10 March 2019	43 days
Designing of component layout	10 January 2019	15 January 2019	4 days
Review 1	14 January 2019	14 January 2019	
Making final CAD model	15 January 2019	25 January 2019	9 days
Ordering of Parts for the prototype	25 January 2019	01 March 2019	26 days
Testing of Electronic Circuit before assembly	01 February 2019	15 February 2019	11 days
Review 2	18 February 2019	18 February 2019	
Building of prototype	20 February 2019	15 March 2019	18 days
Testing final prototype	16 March 2019	01 April 2019	12 days
Measurement of TCD	01 April 2019	05 April 2019	5 days
Calculation and verification of Results	10 April 2019	15 April 2019	4 days
Final observations and optimization	15 April 2019	01 May 2019	13 days
Report modification	06 May 2019	12 May 2019	6 days
Review 3	27 May 2019	27 May 2019	

1.6 Methodology

1. Study relevant literature from reputed journals (SAE, ELSEVIER, etc) regarding four wheel steering.
2. Decide the steering behaviour for the front and rear wheels.
3. Design the steering geometry on SolidWorks 2016 x64 Edition based on the steering behaviour.
4. Decide Motor specifications and calculations of gear ratios.
5. Design vehicle body and mounting of steering and suspension components.
6. MATLAB simulation of steering behaviour.
7. ARDUINO coding for the driving and steering motors & actuators present.
8. Assembly of the model.
9. Testing of the final prototype.
10. Calculation and comparison of turning circle radii as opposed to a conventional front wheel steered vehicle of comparable specifications.

1.7 Conclusion

This section talked about the aim and the methodology which would be followed during the course of the project. The aim shifts to literature survey and reviewing existing work in fields closely or remotely related to the prototype designed. The section also delves into the current steering geometries and highlights some rudimental calculations to depict the concepts.

Chapter 2 Literature and Patent Review on Steering System

2.1 Introduction

Sufficient literature was referred to during the course of the project in order to understand the current rate of progress and the development in this specific field of four wheel steering. While sufficient work has been conducted on two wheel steering and four wheel steering, the work on zero turn steer is limited.

2.2 Types of Steering Geometry

There are various type of steering geometry used for various applications. A steering geometry is the design and build of the linkages that transmits the steering movement to the wheels thereby steering the direction of the car. Various applications call for varied steering geometry which has huge implications on steering characteristics and stability of the vehicle and low and high speed situations.

2.2.1 Davis Steering

Davis steering mechanism is another way of satisfying the geometric conditions required to steer a car while reducing the slippage of the tyres. It utilizes two sliding pairs instead of turning pairs used in Ackermann geometry. As a result, this mechanism is mathematically more accurate. [4]

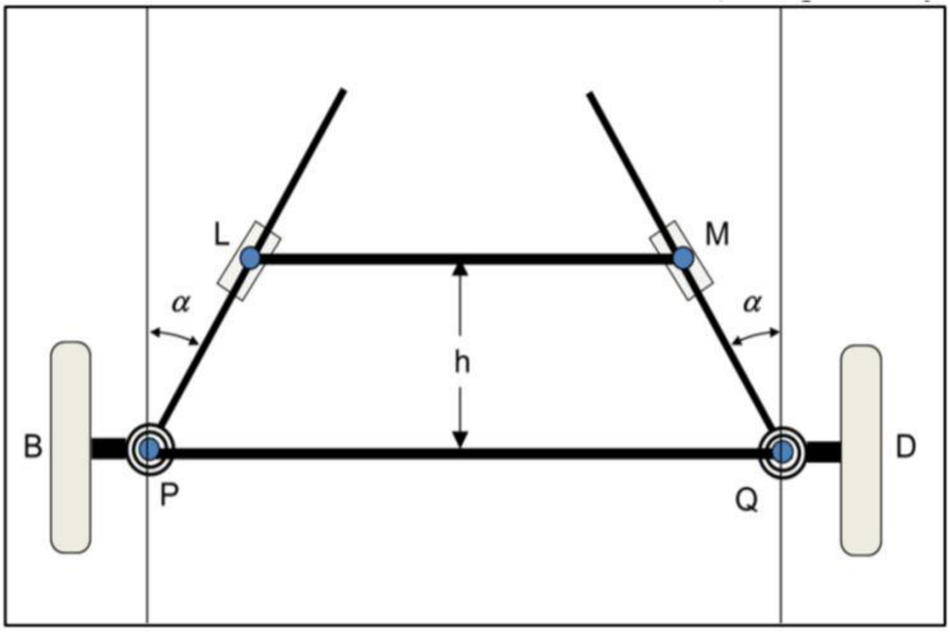


Figure 2.1 Davis Steering **[4]**

2.2.2 Ackerman Steering

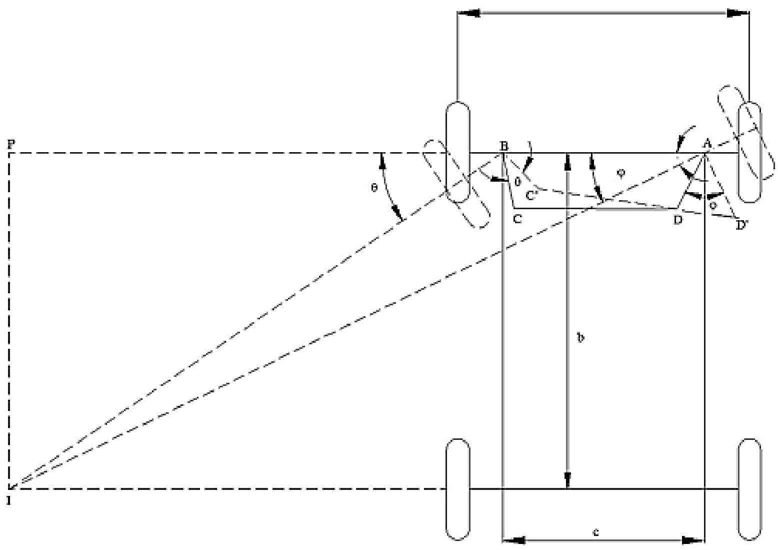


Figure 2.2 Ackerman Steering**[5]**

The Ackermann steering gear consists of a pair of turning pairs rather than sliding pairs (found in the Davis steering mechanism)[4]. In Ackermann steering gear, the mechanism ABCD is a four bar crank chain (as shown). The shorter links BC and AD are equally inclined to the longitudinal axis of the vehicle. The following three positions are found to satisfy the required condition of pure rolling motion of the wheels:

- Motion in a straight line
- Motion at a particular angle on either side of the steering range of motion i.e. the angles that satisfy $\cot(\varphi) - \cot(\theta) = c/b$

In Figure 2.2 it can be seen that the inner wheel projects an angle θ while turning whilst the outer wheel projects an angle of Φ while negotiating the turn. The vehicle possesses a wheel track of 'a', wheel base of 'b' and a distance between the pivots of the two steered wheels at the front axle denoted by 'c'. [5]

2.3 Types of Steering Mechanisms in Vehicles

A system in which the rear wheels also assist in steering the vehicle is called a four-wheel steering system (not to be confused with four-wheel drive). It can be classified into various 'modes' depending on the angle and turn direction of the rear wheels, and how it can be implemented in the vehicle:

2.3.1 Passive Rear Wheel Steering

As the name suggests, passive steering does not really control the rear wheel angle, but allows it to turn by a small angle according to the lateral forces acting on it by using suspension linkages and bushings.

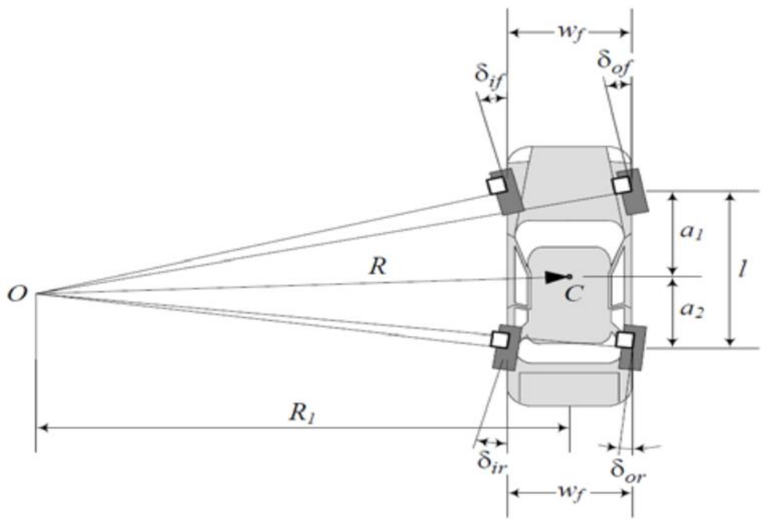


Figure 2.3 Counter-Phase 4WS **[6]**

This effect is called compliance under steer, and is common in high-end passenger vehicles typically implemented by suspension geometry design.Since controllers and actuators are not involved, and the angles of turn are very small, it is not as effective as complete 4W steering. [7] [8]

2.3.2 Counter-phase Four Wheel Steering

The vehicles with ‘active’ 4WS implementation is achieved through the use of sensors, controller and actuators to turn the rear wheels. For counter-phase steering, the rear wheels turn at an angle opposite to the front wheels, as shown in Figure 2.3 where the angle is decided by an ECU based on vehicle speed and steering wheel turning angle. At low speeds, this counter-phase steering allows tighter turning radius. More advantages are discussed in under 4WS section. [8] [6]

2.3.3 In-Phase Steering or Crab Steer

Crab steering or in-phase steering depicted in Figure 2.4 involves turning the rear wheels in the same direction as the front wheels, to increase the lateral stability and lane-changing capacity of the vehicle. At high speeds, this allows more control over vehicle handling and makes quick lane changing much safer. [8]

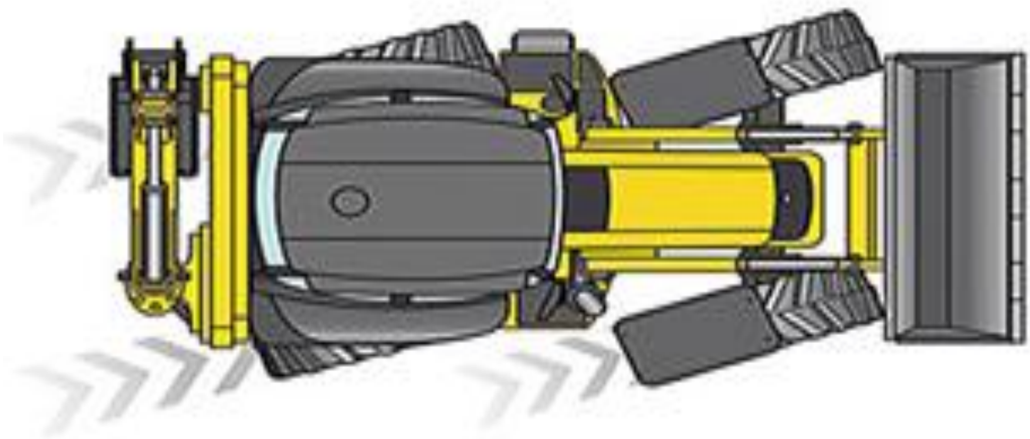


Figure 2.4 Indicating Crab steer Mechanism for an Off-Road Vehicle Where Front and Rear Wheels Turned in the Same Direction **[9]**

2.3.4 Only Rear Wheel Steering

This type of steering system is usually found on special-purpose vehicles like fork lift trucks, camera dollies and early pay loaders. Rear wheel steering tends to be unstable due to the steering geometry thereby increasing the chances of oversteer. A rear wheel steered vehicle turns in the direction opposite of how it is initially steered, making it confusing for the driver. A rapid steering input will cause two accelerations. First in the direction that the wheel is steered, and then in the opposite direction, a sort of reverse response. Above-mentioned reasons make rear-only steered vehicles uncommon in use [7]. Figure 2.5 shows how rear wheel steer works. [8] [7]

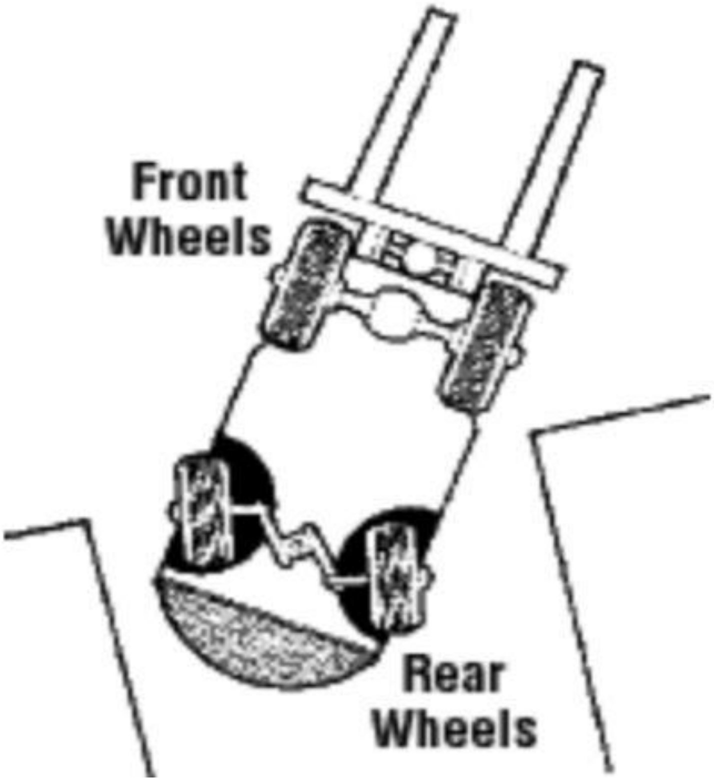


Figure 2.5 Only Rear Wheel Steering For Largely Used In Warehouse Vehicles **[8]**

2.3.5 Zero Turn Steer

Zero turn steering involves changing the wheel angles of the front and rear wheels such that the vehicle can turn about its geometric centre, making the theoretical turning radius zero.

The immense number of advantages this system would potentially provide to the driver are only overshadowed by the impracticalities in its application in a real vehicle, ranging from the opposite-turning wheels on the same axle to changing the direction of rotation of half of the driven wheels [10],[11]. Still, some vehicles have demonstrated this concept like the Jeep Hurricane [12]. The concept of zero turn steer is shown in Figure 2.6.

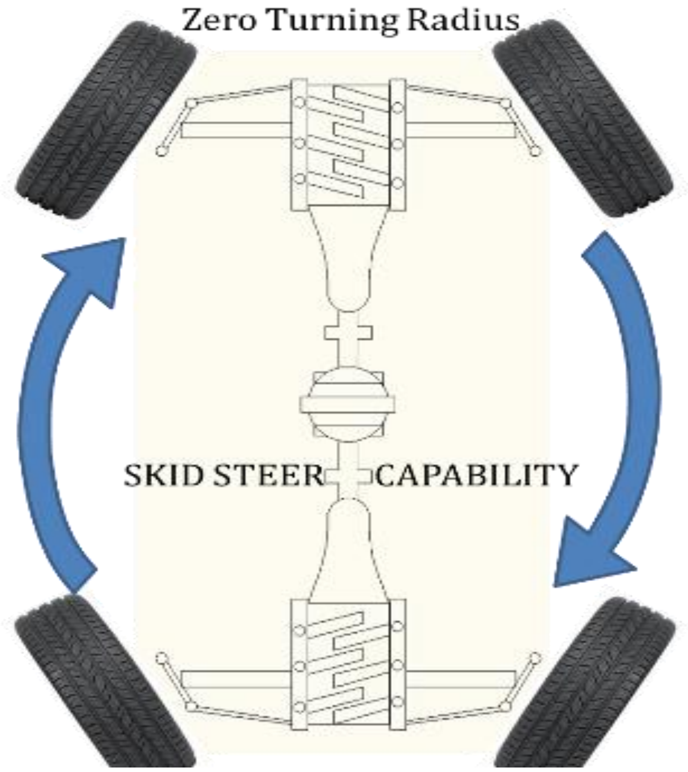


Figure 2.6 Zero-Turn Steer **[10]**

This system comes with numerous advantages. Some of these are listed below [8] [7]:

- Superior cornering: The vehicle can take turns around smaller corners, in roads with lesser width.
- Improved steering response: Since the rear assist is electronically controlled, the overall steering response would be smoother at any vehicle speed.
- High speed stability and lane changing: As the crab steer kicks in at high speeds; the vehicle will feel more stable and in-control while changing lanes can perform this manoeuvre faster.
- Smaller turning radius: The imaginary centre of turning of the vehicle comes closer as the rear wheel turning angle increases out-of-phase, giving a smaller turning circle radius which is helpful in all sort of situations like turning, parking, and backing out of tight corners, manoeuvring in tight spaces and taking U-turns.

However, the advantages are also accompanied by a few disadvantages. Some of these are:

- Chance of electrical and hydraulic failure: This system relies on sensors such as, vehicle speed sensors.

- Also, with a microcontroller and auxiliary electrical components the chances of failure increase.
- Additionally, failures in hydraulic systems are also bound to occur and will need a self-diagnostic circuit which has to be integrated to the system in order to detect the same. [7]
- Space and complexity: Additional components require space, which need to be fitted near the wheel hub and suspension systems, an area which is already crowded.
- Apart from packaging problems, these components increase overall complexity of the system, potentially creating additional failure modes which need to be addressed.

2.4 Steering System

2.4.1 Introduction

The vehicle steering system is a collection of parts that help communicate the steering action by the driver to the road through the pair of steered wheels.

Conventionally, the steered wheels are located at the front of the vehicle. This system guides the vehicle through the trajectory chosen by the driver. This section describes about the various steering systems available and delves into the design aspects of the same.

2.4.2 Requirements

The steering system while possessing simple functionalities, are required to satisfy a wide range of requirements for optimum performance. Some of these requirements of the steering system are as follows:

1. Should prevent the vehicle from wandering off to either ends while traversing a straight line path. The driver should be able to maintain a straight path with minimum or no inputs at the steering wheel.
2. It should offer optimum directional stability. This involves a return to straight ahead position after executing a turning manoeuvre by the driver.
3. It should convey information from the tire-road contact patch up to the driver. This feedback is of utmost importance and helps the driver judgement upon driving on various surfaces at various speeds.
4. Additionally, it must help maintain a desirable contact path between the rubber and the asphalt for optimum traction.

5. The system is also responsible for the angles between the wheels upon turning and during straight line driving manoeuvres.
6. It must enable the driver to steer the vehicle without exerting much force. This is important for reduced driver fatigue, critical during long distance driving and city travelling. On the contrary, the wheel must not be too light to turn, which can result in the vehicle being too hard to control.

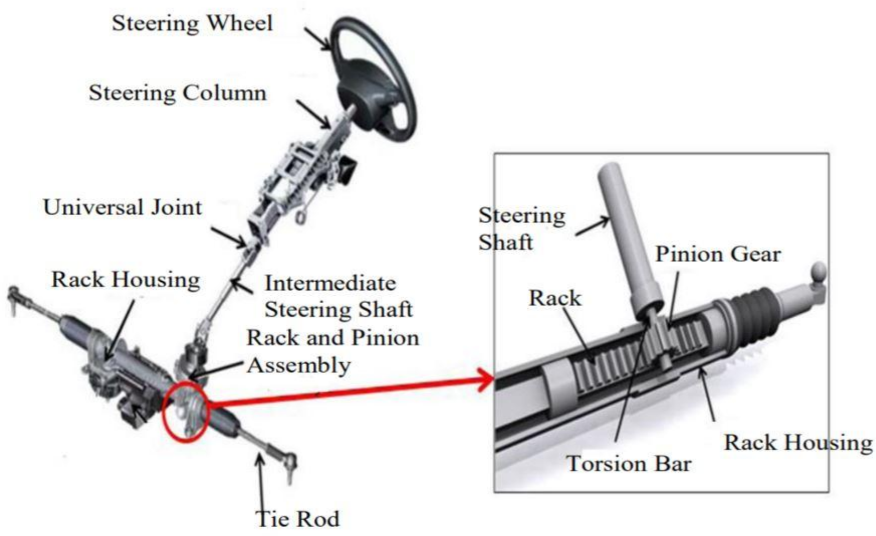


Figure 2.7 Cut Section View of a Conventional Steering Column**[14]**

2.4.3 Ackerman Steering

The Ackerman principle states that if the instantaneous centres of all wheels meet at a point, then the vehicle will negotiate a turnabout that point. This results in pure rolling condition of the vehicle. The Ackerman steering geometry is deployed in vehicles to prevent sideways slip of the tyres upon negotiating a turn. [14]

Geometrically, the solution is presented by having the inner and outer tyres trace out paths of different radii while having the same centre of rotation. To achieve this, the inner wheels turn by a greater angle as opposed to the outer wheels whilst negotiating a turn. While more complex, this steering mechanism enhances the vehicle controllability. It avoids tire slippage and achieves pure rolling. Additionally, this mechanism reduces friction and wear and thus has easy maintenance.[16]

2.4.3.1 Conditions for Perfect Steering

While moving, the perfect steering is achieved when all the four wheels are rotating perfectly under all conditions of running. The prime condition to be satisfied by a steering mechanism while negotiating a turn is that the wheels must turn about the same instantaneous centre while negotiating a curve. This instantaneous centre is ideally located in line with the rear axle of the vehicle. Inability of the wheel to rotate about this instantaneous centre will cause the wheel to slip. For illustration purposes in Figure 2.8 consider that the inner wheel projects an angle θ while turning. At the same time, the outer wheel projects an angle of Φ while negotiating the turn. The vehicle possesses a wheel track of ‘a’, wheel base of ‘b’ and a distance between the pivots of the two steered wheels at the front axle denoted by ‘c’. [17]

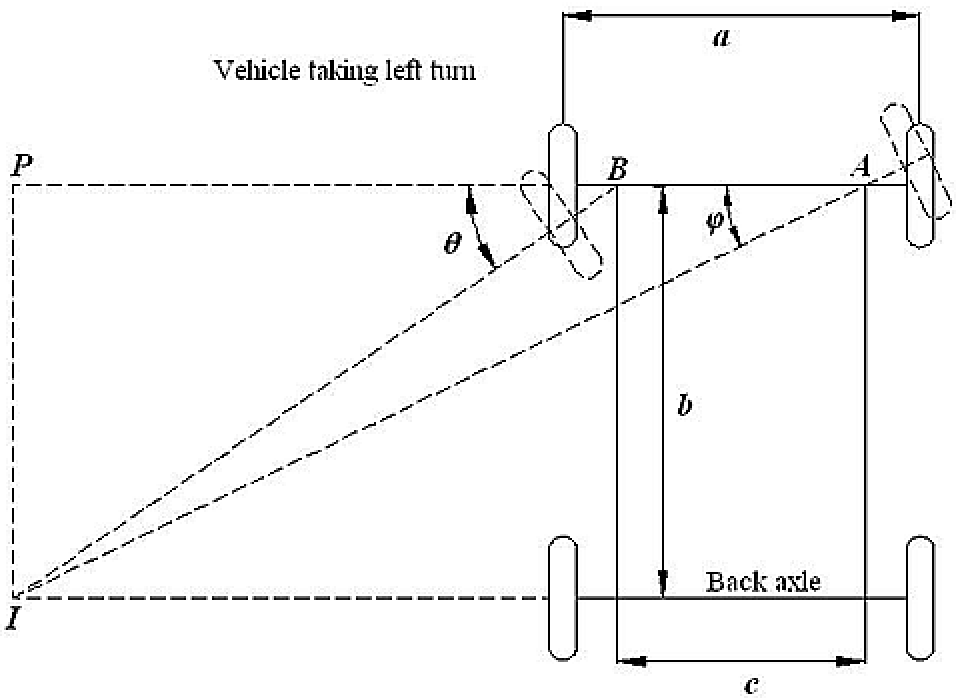


Figure 2.8 Ackerman Steering System**[5]**

From the ΔIBP,

$$\cot\theta = \frac{BP}{IP} \tag{1}$$

Further, from ΔIAP

$$\cot\Phi = \frac{AP}{IP} = \frac{AB+BP}{IP} = \frac{AB}{IP} + \frac{BP}{IP} = \frac{c}{b} + \cot\theta \tag{2}$$

From the above equations,

$$\cot\Phi - \cot\theta = \frac{c}{b} \tag{3}$$

This is the Ackerman condition for two wheel steering. [17]

In the figure RABS Figure 2.9 is a four bar chain mechanism. RA and SB are of equal lengths. These two elements are joint together by a track-rod, denoted by AB.

The angle between the links RA & SB (as shown in Figure 2.9) and the centreline of the vehicle is denoted by α. This is maintained when the vehicle moves along the straight line. The dotted lines in the figure indicates the change in the position of the bar linkages while negotiating a left turn.

AB = l

RA=SB=r

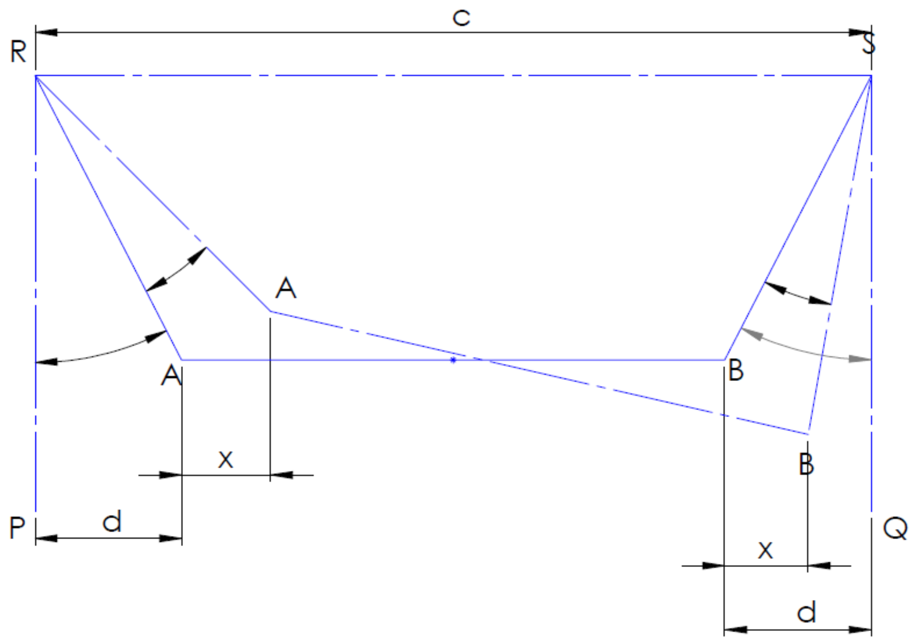


Figure 2.9 Calculation for Ackerman Steering Formula (adapted from **[5]**)

$$\llcorner PRA = \llcorner QSB = \alpha \quad (1)$$

While turned as shown in the figure above

$$\llcorner ARA = \theta \,\&\, \llcorner BSB = \Phi \quad (2)$$

This also indicates the angle turned by the inner and the outer stub axles during the turn. Neglecting the obliquity of the track-rods, A and B traverse the same distance of x in the lateral direction.

Thus,

$$\sin(\alpha + \theta) = \frac{d+x}{r} \tag{3}$$

$$\sin(\alpha - \theta) = \frac{d-x}{r} \tag{4}$$

Adding the two equations,

$$\sin(\alpha + \theta) + \sin(\alpha - \theta) = \frac{2d}{r} = 2\ sin\alpha \tag{5}$$

Important point to be noted here is that this steering mechanism gives accurate values in three conditions only. This is because Ackerman steering geometry is not a perfect geometry as opposed to Davis steering system. They are,

- When the wheels are pointed straight ahead while having θ =0.
- At an angle chosen by steering system designer in both the directions

This is because at every other position, perpendiculars drawn from all the tyres do not exactly meet at a point whereas Davis steering mechanism is able to achieve this condition at all angles of toe

2.4.4 Types of Steering Gearboxes

Vehicle of the past have used various types of steering gearboxes to transfer the rotational motion of the steering wheel by the driver onto the subsequent mechanical linkages and ultimately the wheel. A few of these are as follows:

- Rack and Pinion Steering Mechanism
- Recirculating ball Steering Mechanism
- Worm and Gear Steering Mechanism

However, the most common among them is the Rack and Pinion steering wheel mechanism. This mechanism is now most common on passenger vehicles and commercial trucks.

This steering gearbox is relatively simple and converts the rotation of the steering wheel by the driver to a straight line movement at the wheels. The main components in this type of steering gearbox is the rack, pinion and the gearbox housings along with the bearings involved for reduction in friction.

The rotation of the steering wheel rotates the pinion located at the end of the steering shaft. The pinion is in constant mesh with the steering rack. Hence as shown in Figure 2.10, the movement of the pinion causes a movement of the rack, thereby moving the tie-rods located at either end to rotate the wheels.[18]

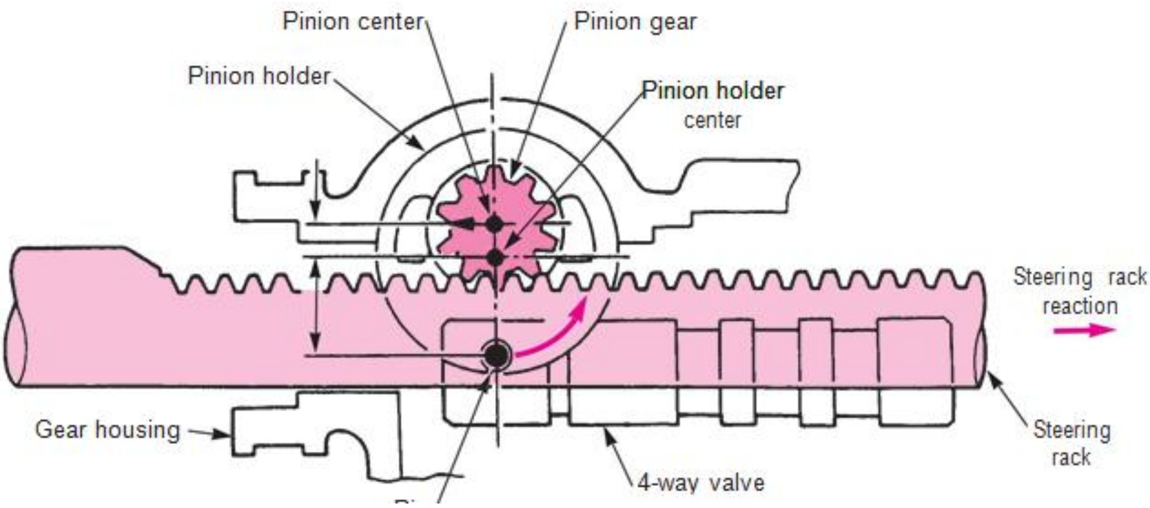


Figure 2.10 Rack and Pinions Steering Gear System **[18]**

The aluminium body of the rack and pinion casting is generally mounted using brackets onto the vehicle frame. A series of bolts and nuts are generally used to mount other auxiliary parts through holes in the rack body and the vehicle's frame. The pinion assembly is a hardened steel gear supported by bearings at the top and bottom. Seals keep the steering gear lubricant from leaking out of the rack-and-pinion assembly [18]. The pinion is a toothed or worm gear that meshes together so that the arrangement can be moved in either direction by changing application of force on the steering wheel [19]. The rack and pinion steering system can assist hydraulically or using electric system. The system can vary the progression of the steering wheel turn but can also deliver a non-linear steering property. [20]

A programme was built on MATLAB to determine the turning circle radius when the essential data regarding the vehicle dimension as input variables. This information includes:

- Wheel Base
- Wheel Track
- The Front inner wheel (or) Outer wheel maximum turning angle
- Scrub Diameter

The MATLAB code and output is explained in length in Appendix 1.

2.5 Four Wheel Steering Mechanism and Design

The problem discussed in this project work is with relation to the four wheel steering mechanism. In a four wheel steering mechanism, all of the four wheels turn at various angles in various angles dependent to other wheels or in complete independence; to achieve improved steering performance of the vehicle.

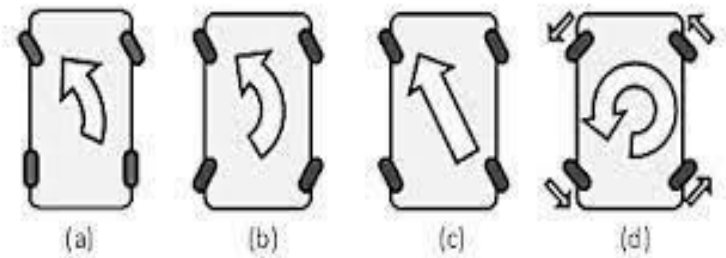


Figure 2.11 Types of Wheel Steer (a) Conventional steering (b) Counter-phase steering (c) crab steer (d) Zero Turn Steer **[10]**.

Here, various types of steering mechanisms are introduced. Further detailed design report is presented about the mechanical, hydraulic and the electric build of the prototype. This section details about the design and the assembly of the vehicle as well.

There are various types of four wheel steering mechanisms, each indicated by Figure 2.11.

2.5.1 Four Wheel Steer or Counter-Phase Steering:

This has the rear two wheels rotate in a direction opposite to the front two wheels. Such a mechanism helps with low speed manoeuvrability of the vehicle. It drastically reduces the turning circle diameter and helps with navigating around tight corners and parking spaces.

2.5.2 Crab Steer or In-Phase Steering:

The crab steer accounts for the high speed stability of passenger vehicles. In this type of steering mechanism, the rear two wheels turn slightly in the same direction as the front two wheels thereby allowing the vehicle to negotiate a high speed turn or lane changing with minimal instability caused in the process. [7] Refer Figure 2.12 for illustration.

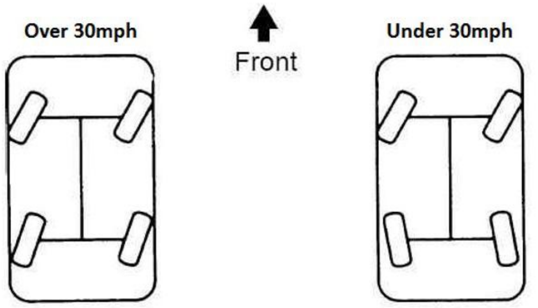


Figure 2.12: Difference in working of 4WS at In-Phase And Counter-Phase Applications**[2]**

2.5.3 Zero Turn Steer:

This rotates all the tires to the opposite direction to its laterally opposite tire. This enables the vehicle to rotate about its own axis. This can help with turning very fast at dead ends or turning through specific angles. This rotation about its own axis is accomplished by deploying a toe-in on all the wheels. This forces the centre of rotation to be at the centre of the Vehicle.

- Advantages of Zero Steer Mechanism:
  1. Improved manoeuvrability
  2. Ability to turn 180 degrees instantly.

- Disadvantages:
  1. Added cost
  2. Added complexity
  3. Improved chance of wear due to greater number of involved parts

Figure 2.13 Jeep Hurricane Concept which Features Zero Steer **[12]**

2.6 Relation Between Steering Wheel Angle and Road Wheel Turning Angles (Front and Back)

At low speeds, the 4-wheel turning allows for tighter turning, and at higher speed the crab steer makes the vehicle more stable while changing lanes.[22]. However, since this project is aimed at low speed applications, crab steer is not of utmost priority and little work is done in this respect. To decide if the turning should be normal 4-wheel steer or crab steer, the angle turned by the rear wheels as a function of vehicle speed can be measured, or a function of front wheel turning angle [23]. At low speeds, when tighter turns are needed, a typical driver turns the front tyres as much as possible for the maximum turning space efficiency. Conversely, at high speeds the steering is turned only a little to shift lanes or turn at a large radius as the road bends. So it becomes convenient to use the front steering angle as a parameter in the function that controls the rear wheel turning angle. [18]

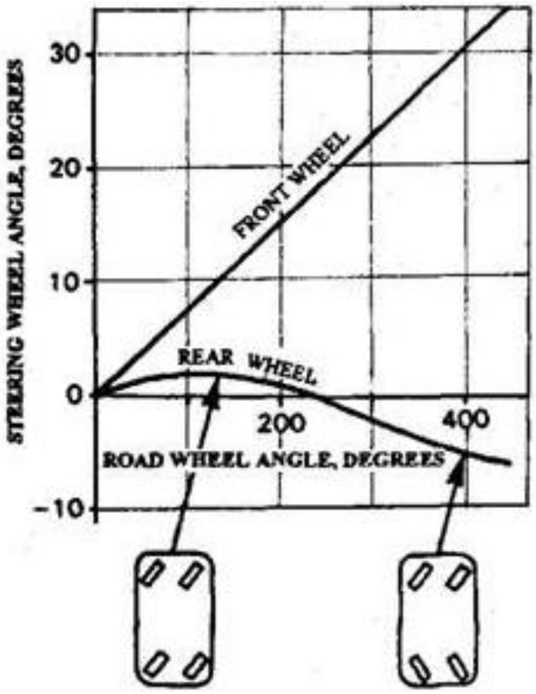


Figure 2.14 Relation Between Steering Wheel Angle And Road Wheel Turning Angles (Front And Back) **[18]**

To generate that function, following constraints should be considered:

a) The rear wheels should turn with the front wheels to certain angle, then turn in the opposite side when the angle is increased above a certain value
b) The change in turn direction should not be too sudden

c) The rear wheels should never turn more than the front wheels in the same direction, as that would cause the car to turn in the opposite direction as intended.

Consulting existing literature, and using a curve-fitting tool in MATLAB, a 4th degree polynomial is generated for Figure 2.14 from a set of points which the rear wheel angle should suffice when the front wheel angle is at a particular value. This graph that portrays the relation between the steering wheel angle and the road wheel turning angle is shown in Figure 2.14. [23]

This graph helps draw a conclusion between the relationship of the front and the rear wheel turning angles. This value can be input into MATLAB for simulation using polyfit function and can help in determining the stepper wheel angles with relation to the servos using arrays in Arduino IDE

2.7 Conclusion

The chapter described the working of the steering system and its types. It explains the conventional rack and pinion type steering arrangement which is still widely deployed in modern road cars, albeit in various specifications and a wide variety of designs. After a thorough literature review, it was found that various modes of steering the rear wheels in conjunction with the front wheels maybe used to obtain improvements in manoeuvrability in the desired way. Various mechanisms maybe used including Ackermann or Davis mechanisms in order to satisfy geometrical condition of steering the vehicle without tyre slippage rear wheel maybe used in one of the following configurations:

- in phase to have safer high speed manoeuvres like lane shift
- counter-phase to achieve shorter turning circle radii
- zero turn steer maybe used to point the vehicle in the opposite direction while requiring minimum space

During the review of literature in this field it was seen lacking in a research paper thoroughly describing the design process one must undergo to construct a working scaled prototype to realise all the functions of a four wheel steered system that can perform a zero turn steer as well. An attempt was made to fill this gap with a paper published in the Journal of Emerging Technologies and Innovative Research (please refer Appendix).

The next chapter delves into the design and build from a mechanical, electrical, electronic and a hydraulic point of view. It details the concepts involved in building the prototype.

Chapter 3 System Design and Development

3.1 Introduction

This section details the complete design and development of the prototype. The section first describes the challenges faced on mechanical front, followed by the electronics and the hydraulic build of the vehicle. The concepts discussed in the previous chapters have been implemented in practice.

3.2 Mechanical Design and Development

The model was developed on SolidWorks 2016 x64 Edition in three iterations. The first stage of design commenced with an emphasis on the rear end of the working prototype. This was decided to be a completely electric build. The rear end was iterated and a decision was made among designs involving option such as placement of the flange bearings, servo motors, moving shafts and mounting positions. Subsequent sections will describe the iterations carried out in the project.

3.2.1 Rear End Design

The rear end design was largely driven by the position of the servo motors, its shafts, DC motors and the wheel hub. The wheel diameter also played a role in deciding the ride height of the vehicle.

As shown in Figure 3.1, Servo motor was set to rotate a rotating disk, with an attached shaft. The shaft was mounted onto the DC motor bracket, which causes the wheels to turn. The design concept is depicted in detail in the Figure 3.1.

The rear end frame length was decided in such a way so as to leave just enough space between the DC motors, especially at their closest point of interaction which is during straight ahead position.

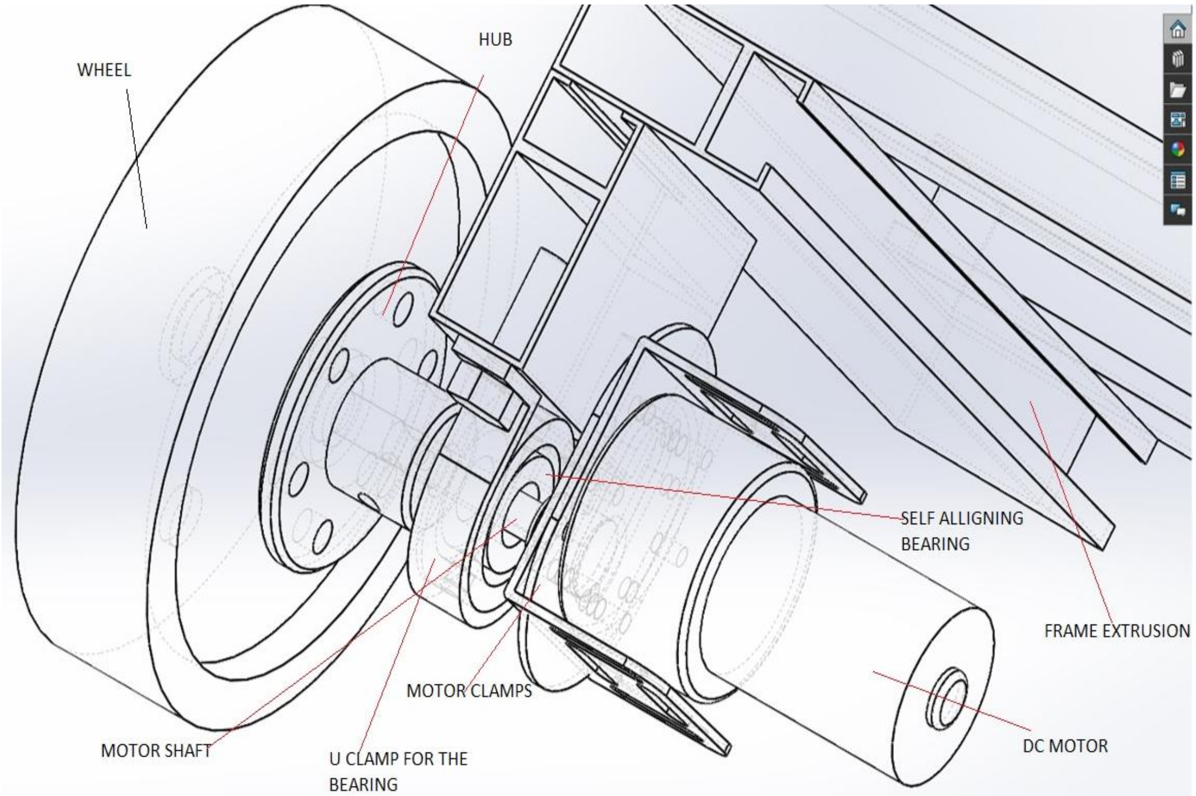


Figure 3.1 Original Rear Design Bottom View

The original design was flawed due to heavy parts and disability to achieve steering motion at the rear end. The huge block above the flange bearings were eliminated. The new design saw the addition of dowel pins for the addition of height.

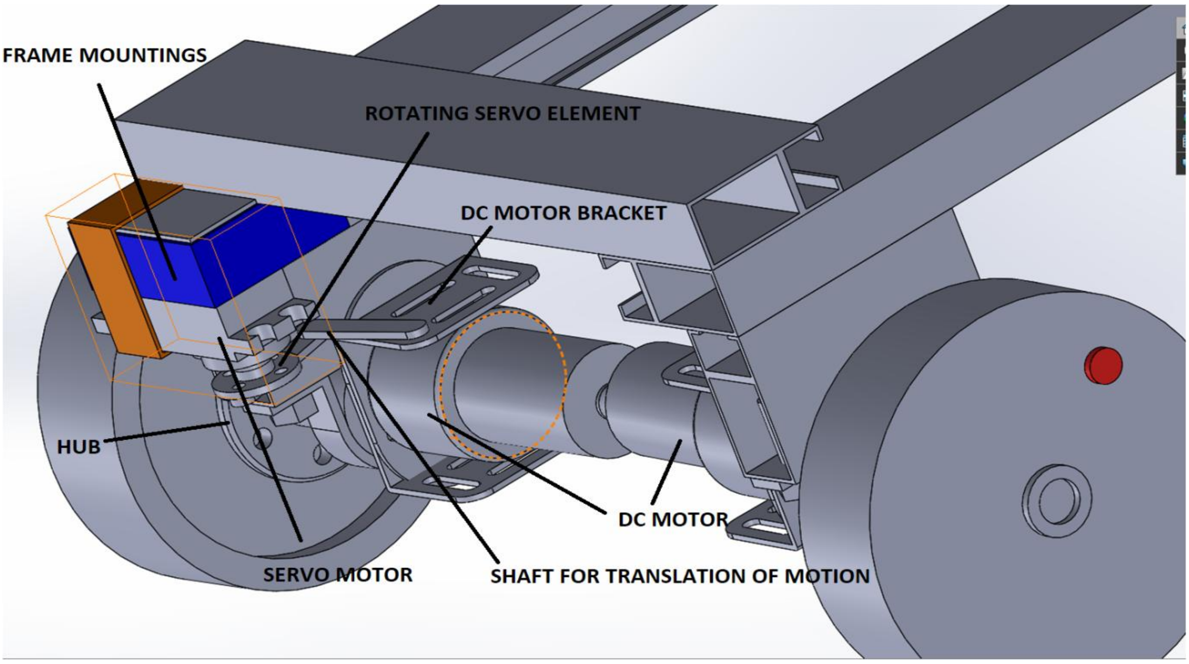


Figure 3.2 Iteration 1 Top Three Quarter View

A dowel pin of 10mm diameter and a height of 40mm were decided for the rear end. This was necessary to have the rear end in level with the front end. Also a ring shaped coupler as shown in Figure 3.2 was used to change the direction of the rear wheel. However, this design was deemed too complicated and could lock the rear wheels much easily.

The second iteration saw the servo motor is mounted on the side member and coupled with a 4 bar mechanism. This mechanism saw two parallel shafts forming a parallelogram shaped movement to assist with the steering [25]. This was doubled on both sides.

The complete iteration 2 is depicted in Figure 3.3. The flange bearings shown in above mentioned figures allows for the bottom end to rotate freely without any friction while mounting the top end to the frame. This enables a revolution of the steering about the dowel pin axis.

Final CAD design was iterated with three major changes. These changes were made due to the excessive ride height of the previous designs. Additionally, the block limited wheel turning angles.

Also, the servo motor mounting posed various challenges for packaging. These changes included a reduction in the dowel pin height of 5 mm. Henceforth, all dowel pins assembled possessed a height of 35 mm throughout the prototype.

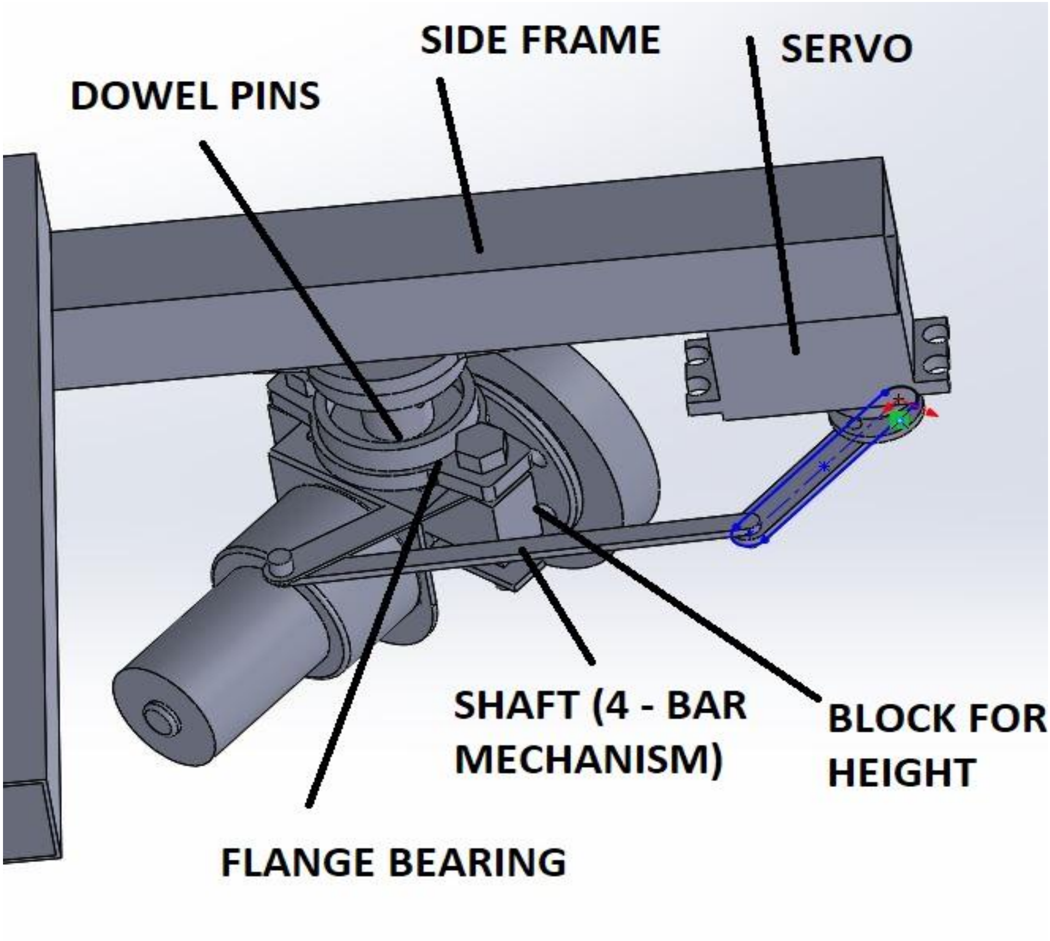


Figure 3.3 Iteration 2 Side servo Mount With 4 Bar Mechanism

Secondly, the block shown in iteration 2 was removed and discarded. Sufficient height was achieved without the use of the block.

Lastly, the servo mounting position was shifted to the rear most frame element. This allowed for a tighter neat packaging of the electronics and the hydraulics, reduced vehicle length and ultimately a smaller working prototype.

Final build of the rear end is seen as depicted in Figure 3.3. The rear end was built as close to the CAD model as possible and was tested for proper functioning. Figure 3.5 shows the stages of development throughout the process and Figure 3.6 shows the final build juxtaposed with the CAD design.

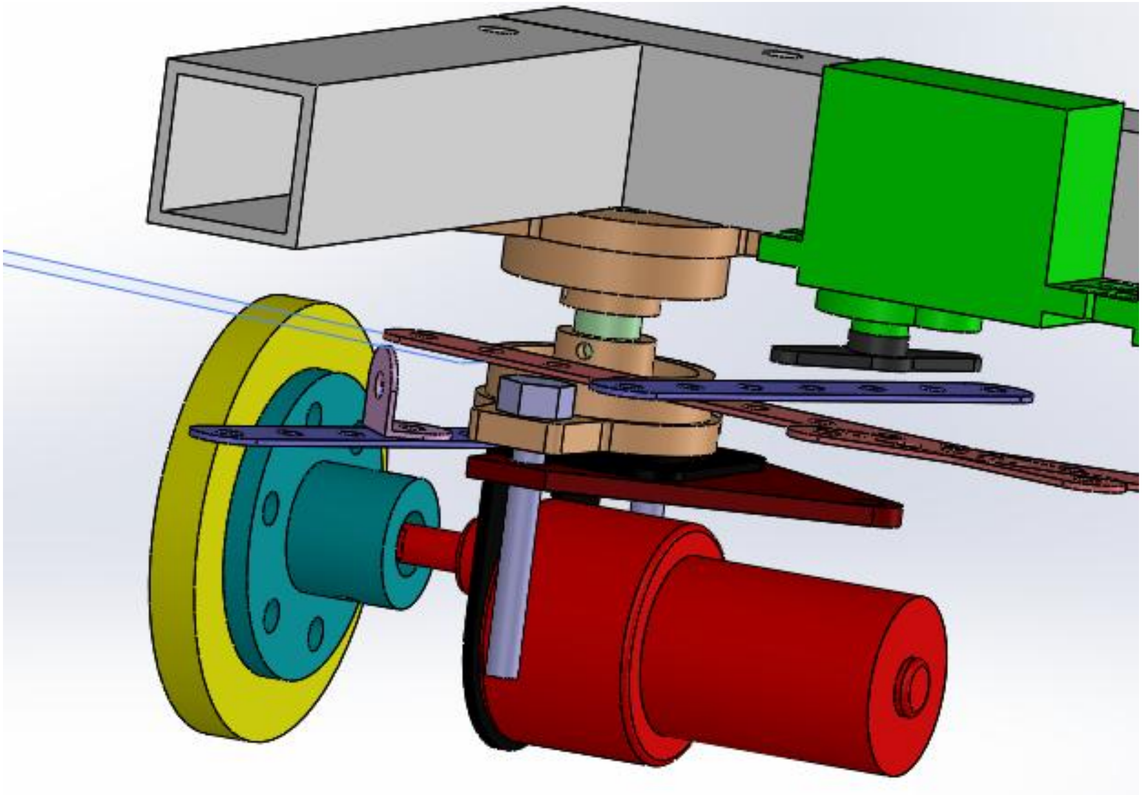


Figure 3.4 Iteration 3 Final Rear End CAD with Servo Mount On The Rear Frame Member

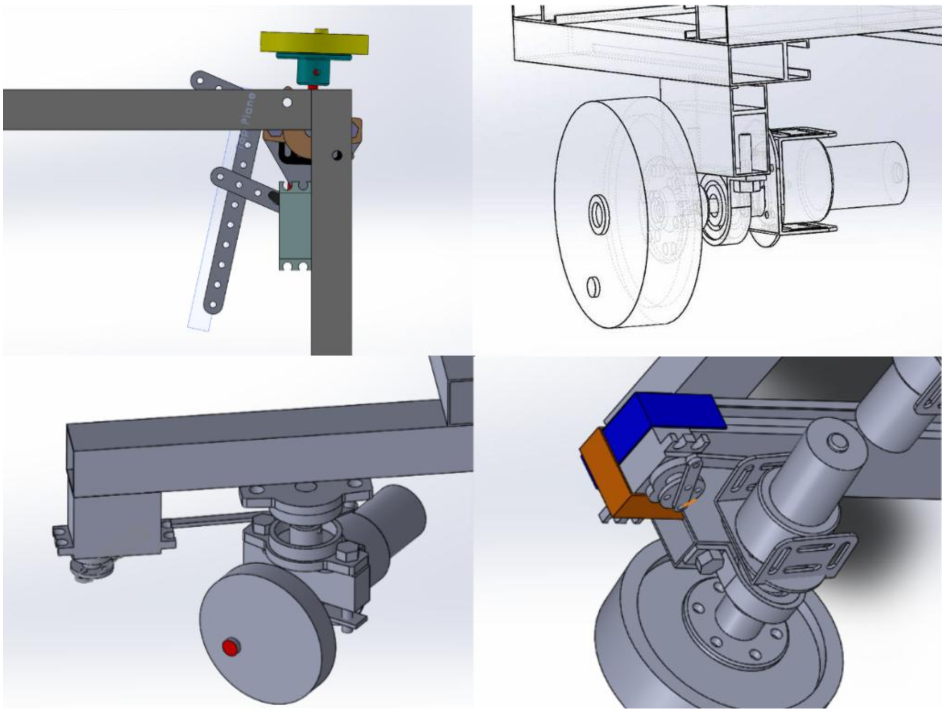


Figure 3.5 Iterations for the Rear End. Oldest, Starting Clockwise from Top Right

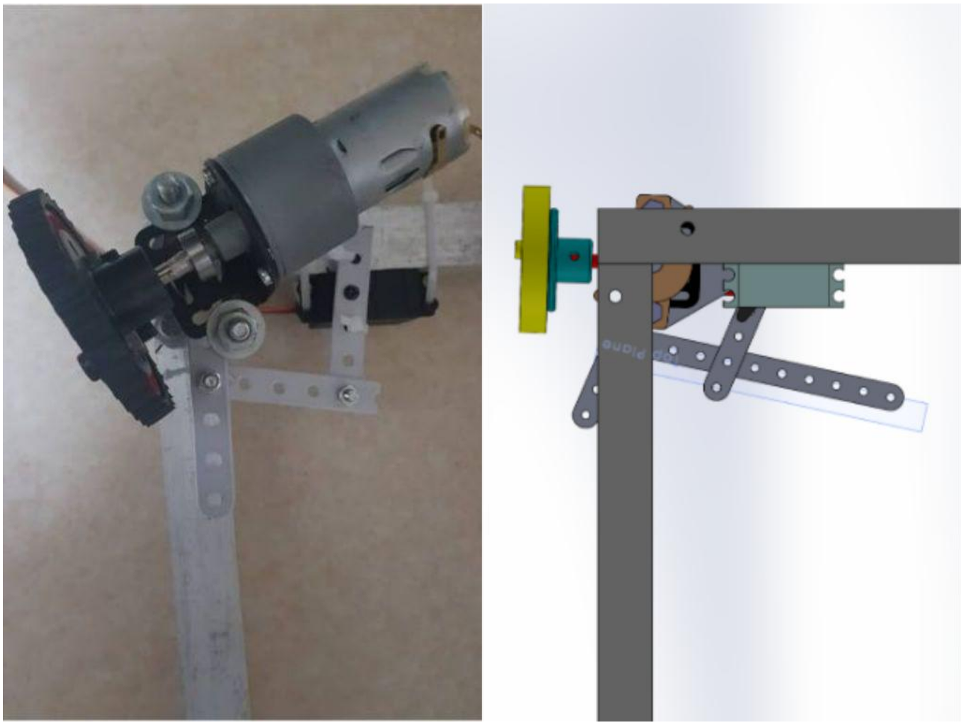


Figure 3.6 Rear End Assembly (a) Left: Final Build (B) Right: CAD Build

3.2.2 Front End Design

Having had the rear end designed full of electronics, the front end was decided to have a combination of mechanical and hydraulic layout. The decision was made to make a rack and pinion system coupled with a hydraulic system to enable zero steer. Unlike the rear end, the front end was developed with just one motor. The stepper motor is to depict a steering wheel.

Turning the wheel by the driver or the user can turn a rack, just like a conventional steering system. This mimics an actual vehicle. However, for a low speed application like a wheel chair, it would be a better choice to have four electric motors due to reduced complexity

As depicted here, unlike the conventional rack and pinion the proposed rack and pinion system is divided into three parts to enable zero turn steer. The three segments can work independent of each other. During zero turn steer, the hydraulics is fully extended and the wheels turn inward on both the sides. This causes the right wheel assembly to behave opposite to the left wheel assembly, while the stepper and the centre wheel assembly stays stationary. Figure 3.7 through Figure 3.8. shows the final front end assembly.

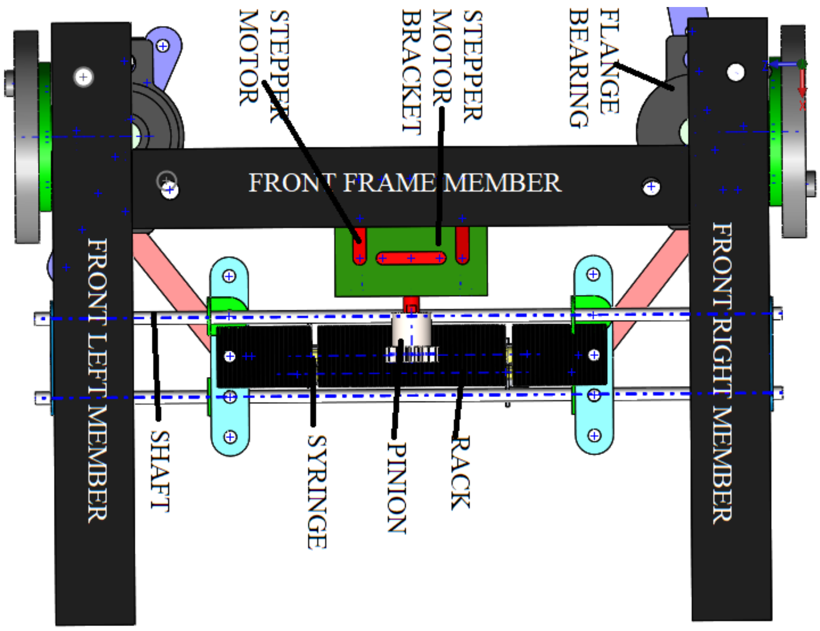


Figure 3.7 Front Assembly – Top View

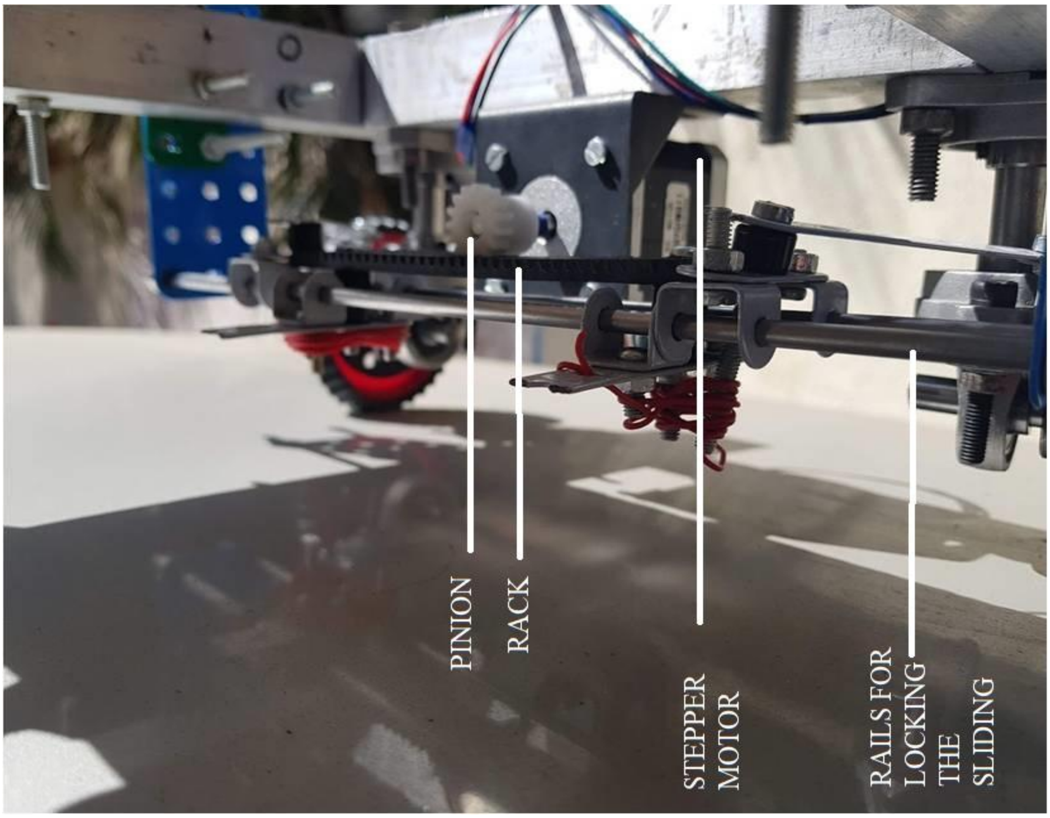


Figure 3.8 Front End Assembly

3.2.3 Front End Geometry

The Ackermann steering geometry for this prototype was designed with three main goals:

- The wheels must be able to toe-in sufficiently attain zero steer conditions when rack is extended
- To have the appropriate amount of toe in on the outer wheel upon maximum lock of inner wheel during turning.[18]
- Wheels must point straight ahead when the rack is centred

Keeping these points in mind the appropriate wheel base to wheel track ratio is determined for the prototype from the existing wheelchairs available in the market with the ratio being as close as possible to 1.5. This benchmark was set since the range of motion of the wheels about its axis was limited and could not exceed 56.3. It was found that popular wheelchair manufacturers adhered to wheelchair design guidelines provided by WHO. In this document it was mentioned that the maximum width of the wheelchair measured from the outer surface of the wheels must be 660mm or 26 inches. Also the maximum length of the wheelchair including overhang for the footrest is 1026mm or 46 inches. With a wheelbase to track width ratio of 1.5, the wheelbase would be 39 inches with a 7 inches of overhang for the footrests which is a reasonable assumption. [25]

Hence, the proposed ration of 1.5 seemed feasible. It was determined that a minimum width of 180mm would be required to fit all the motors and hence the appropriate length of the prototype was found to be 270mm Since the base frame size and pivot points had been established, the project went through various iterations during design phase to determine the optimum link lengths that would geometrically help achieve the goals stated above.

The input variables were:

- Rack length
- Tie rod length

Distance and position of tie rod at the wheel end relative to wheel pivot points was varied using SolidWorks 2016 x64 Edition 2016 x64 Edition, the following trends with respect to input variables was established while the other variables are kept constant. Using SolidWorks 2016 x64 Edition, the following trends with respect to input variables was established while the other variables are kept constant:

a) Increase in Rack length, Decreases Max toe in, Increases 4WS Ackermann compliance, tyres are Toed in Straight ahead condition

b) Increase in tie rod length, Increases Max toe in, Decreases 4WS Ackermann compliance, tyres are Toed in, Straight ahead condition
c) Increase in distance from pivot point, Increases Max toe in, Decreases 4WS Ackermann compliance, tyres are Toed in, Straight ahead condition
d) Increase in angular displacement Increases Max toe in, Decreases 4WS Ackermann compliance, tyres are Toed in, Straight ahead condition.

Table 3.1 Steering characteristic trends with respect to input variables

Increase in (*)	Max Toe in	4WS Ackerman Compliance	Straight Ahead Condition
Rack length	Decreases	Increases	Toed in
Tie rod length	Increases	Decreases	Toed in
Distance from pivot point	Increases	Decreases	Toed in
Angular displacement	Increases	Decreases	Toed in

An ideal design of the final front steering geometry was agreed upon which achieves all the goals outlined in Table 3.1 is drawn in Figure 3.9.

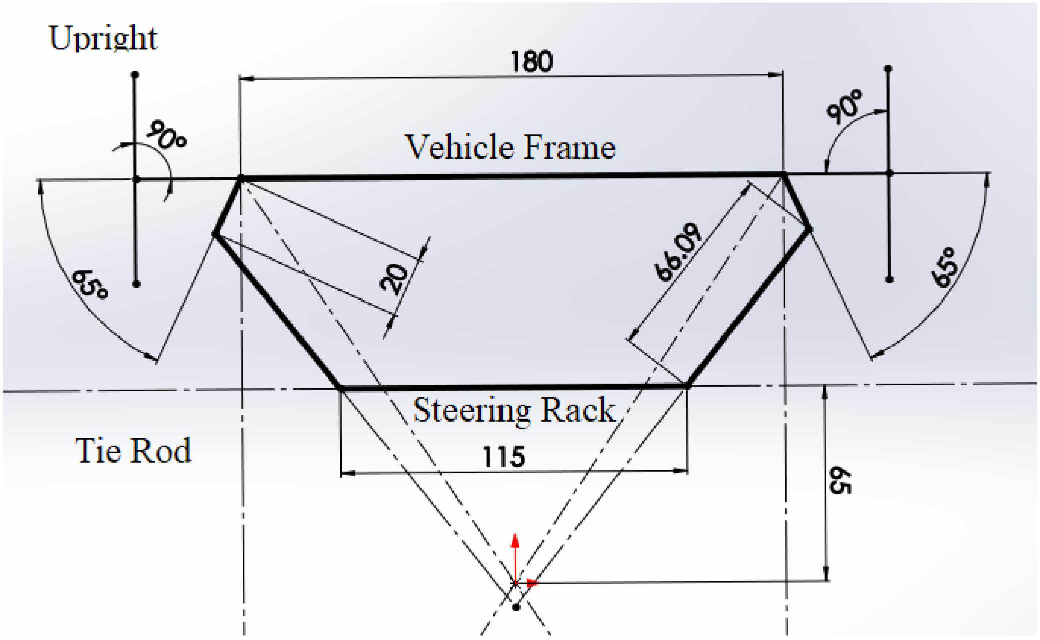


Figure 3.9 Steering Geometry of the front end of the prototype

3.3 Electronics Design and Development

As discussed, the prototype is a culmination of mechanical, electrical, electronic and hydraulic design ideologies. The prototype has multiple electronic components. A huge percentage of these components are used to achieve independent turning of the rear wheels.

Hence a host of motors, drivers and microcontrollers have been tested and programmed to achieve the desired functionalities. The electronic components fulfill the following functions in the model:

- Allow the vehicle to move linearly.
- Make rear wheels turn at independent angles.
- Make front steering geometry turn any required angle.
- Control the timing, degree and duration of every actuator movement thereby deciding vehicle motion and path.

3.3.1 Electrical Components Overview

Numerous components have been used in the our electrical system. Their application and the need have been detailed in Table 3.2.

Table 3.2 Components, Application and Requirements

Component	**Application**	**Requirement**
DC motor	Hub Motor	Holding constant speed, easy to control, economical
Servo motor	Rear wheel steering	Precise position control, 180˚ movement, no driver needed
Stepper Motor	Front geometry steering	Holding torque, precise position control, wide range of motion
Arduino UNO	Controller board	Well documented, economical, enough INPUT/OUTPUT pins
L298N driver	DC motor & stepper motor driver	Current Capacity, documentation and Arduino compatibility, economical

The following were the list of the electronics used in this project.

1. 2 X Arduino UNO board – 5V microcontroller to control all electronic components
2. 2 X DC wheel motor X 2

3. 1 X DC motor for hydraulics control
4. 2 X Servo motor X2
5. Stepper motor
6. 3 X L298n driver – Controlling DC motors and the stepper motor
7. Joystick for motion in +Y and –Y directions
8. Linear slider for motion in +X and –X directions

DC Wheel Motors

The model is rear-wheel drive, for which two brushed DC motors are used to replace hub motors to run the wheels. However, they can be used as hub motors as well to achieve the same function. The DC motors are rated at 100 rpm speed at 12V voltage, and are powered using a single L298n driver. Using PWM, it is possible achieve accurate speed control of the DC motor. This can be altered by specifying values against 255 (since the Arduino UNO is an 8 bit microprocessor) in the Arduino code.

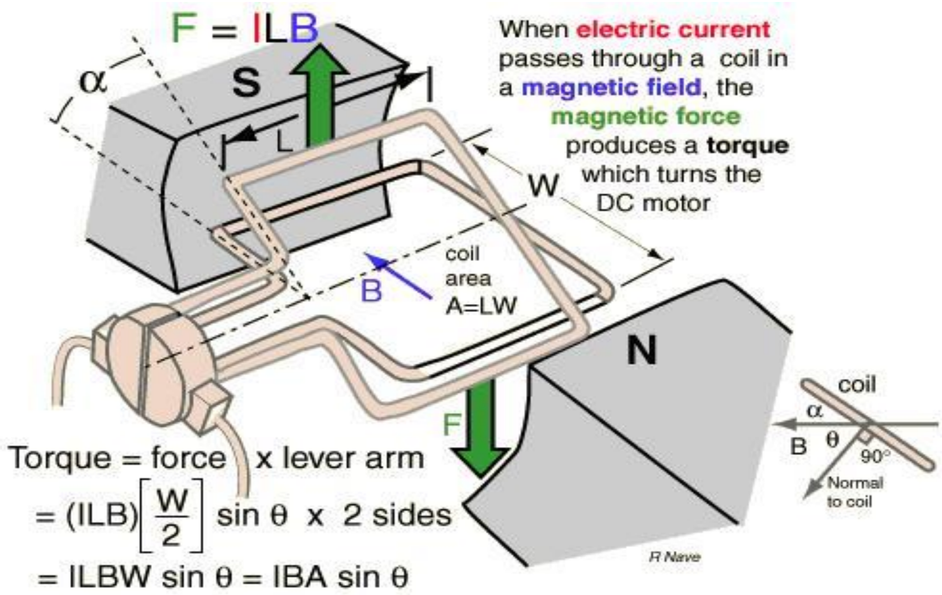


Figure 3.10 DC Motor Internals **[27]**

Servo Motor

Each rear wheel is turned at the desired angle by being coupled with a servo motor, which is a DC motor with bundled controller circuit which tracks shaft position and angle. The motor can be directed to any angle between 0 to 180^{O}. It is possible to achieve up to one degree control of turning on the servo motor.

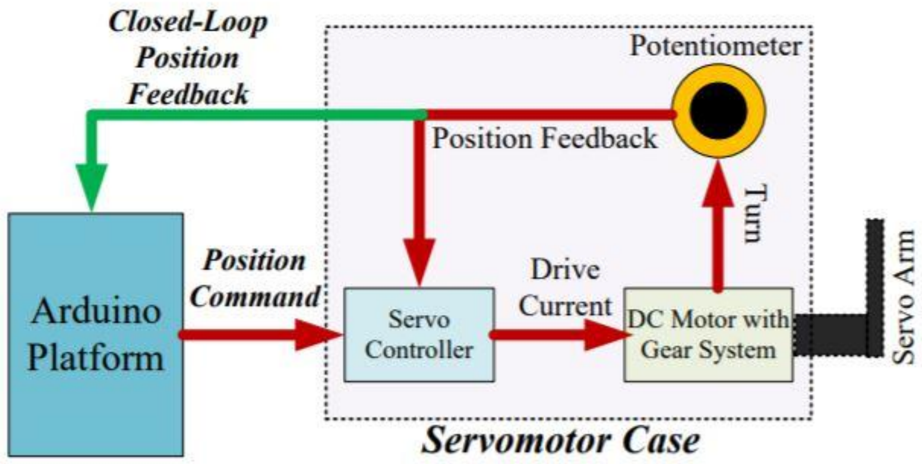


Figure 3.11 Block Diagram of DC Servo Motor **[28]**

Stepper Motor

A 2-phase stepper motor was selected to turn the rack-and-pinion geometry, allowing to steer the front wheels. The single shaft 4.8 Kg-cm torque motor has adequate holding capacity and 200 steps per revolution allow for a least count of 0.23 mm linear movement in the rack. This is calculated by measuring the full rack travel and the degree of turns in the stepper per step. Stepper motor provides large starting, stopping and reversing torque. The motor also has high accuracy and has very high torque output.

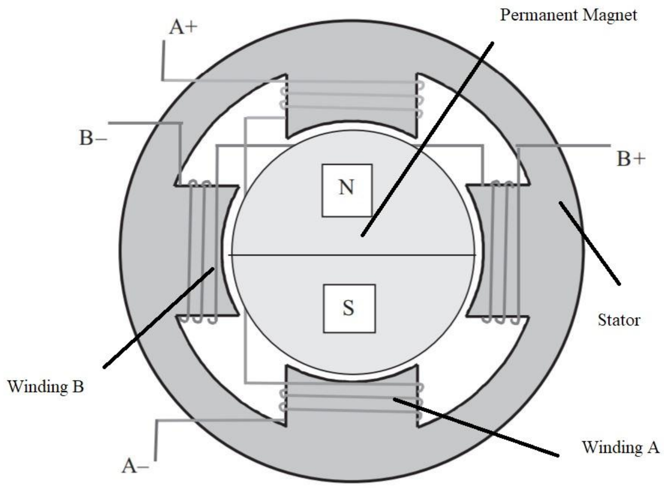


Figure 3.12 Stepper Motor Internals **[29]**

Arduino UNO

The Arduino UNO is a 5V microcontroller development board which runs the algorithm to direct the vehicle path and controls all the electrical actuators:

- DC motor driver
- Stepper motor driver
- Servo (rear right and left)

It can be interfaced with a computer to change its program, and can support any sensors/actuators which might be added later.

Figure 3.13 Arduino UNO – Microcontroller Development Board With 8-Bit And 166mhz Microcontroller Used For the Control of Electric Motors

L298n Driver

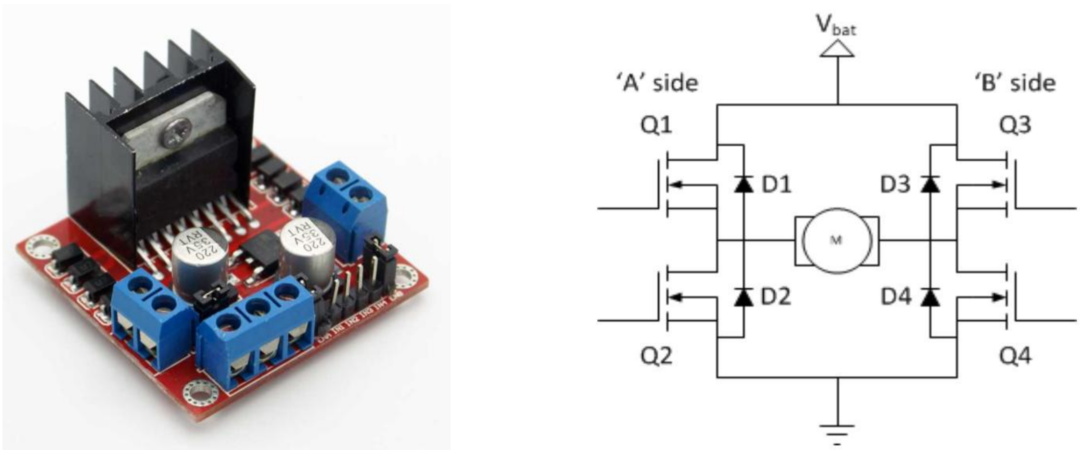


Figure 3.14 L298 Motor Driver for the control of DC Motors, Servo and Stepper Motor (a)L298n Motor Driver (b) Internal Configuration - The H Bridge **[31]**

The L298n driver module is an H-bridge coupled with current protection and a heat sink as in Figure 3.14. The H-Bridge is a switching circuit that contains four switching elements. The load is at the center and all the components are arranged in an H like configuration. Having two H Bridges, it can control two DC motors, or a single stepper motor (since stepper motor has four input pins) using PWM input from a microcontroller. [30]

The L298n driver can accurately control DC motor speed and direction, and stepper motor step movement and stepping speed. The L298N is used here over L298, due to the current carrying capacity of L298N.

Joystick

A joystick is added to the prototype for remote control of the vehicle. The joystick is shown in Figure 3.15 and its working is explained. The Arduino code used is also detailed in Appendix 2.

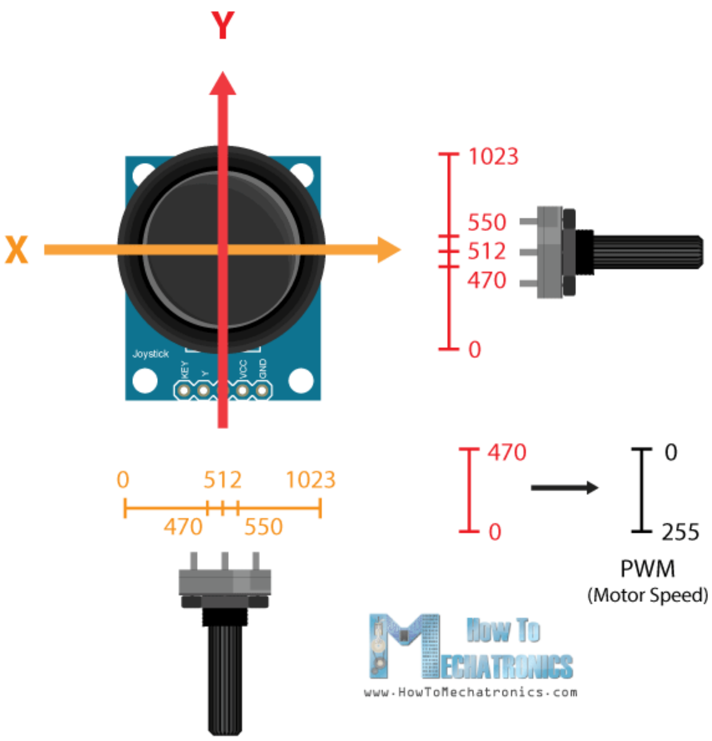


Figure 3.15 Joystick and its Inner Working

Arduino being able to convert analog input to 10 bit digital input, the joystick has 1023 distinct input steps between the minimum and the maximum, with 512 being the midpoint. A joystick module has 5 pins. Namely they are Voltage Pin. X-Axis Pin, Y-Axis Pin, Ground and a pin for the Button. By configuring them on Arduino IDE as per the needs, the prototype can be controlled remotely. The joystick works in tandem with the linear slider, which is also a potentiometer.

The joystick and the linear slider, which is also a potentiometer, are assembled together on a control unit. This can be controlled by the user and can steer the vehicle, put it into zero steer as well as move the vehicle forwards and backwards. The working of the linear slider is detailed below.

Linear Slider

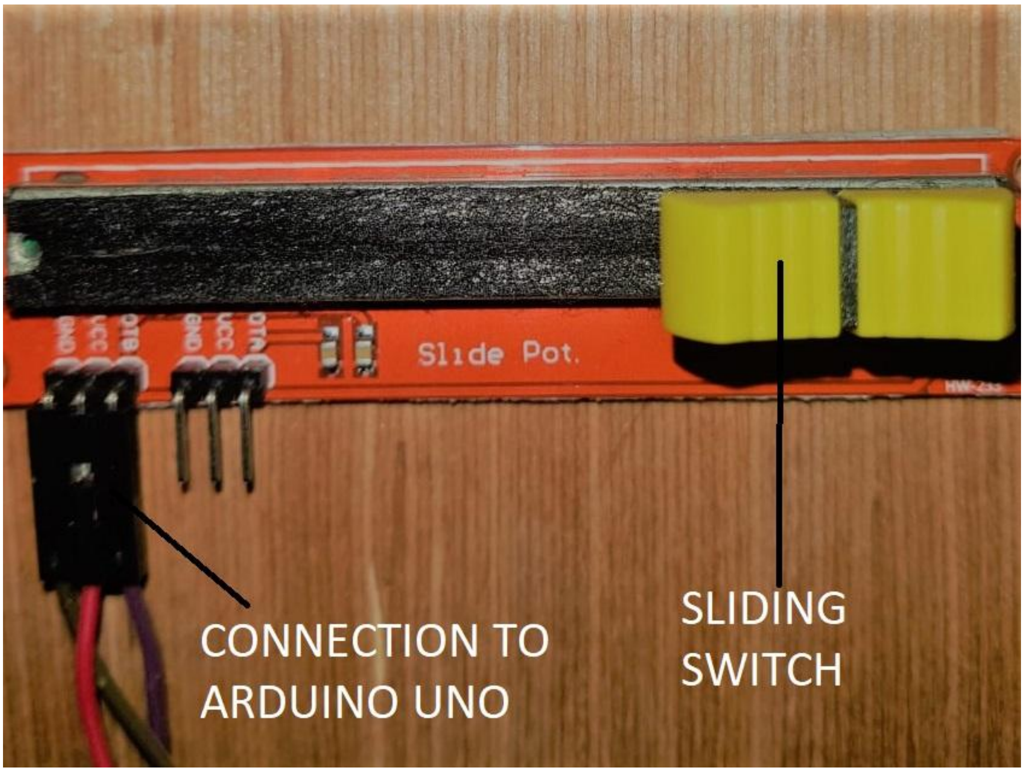


Figure 3.16 Linear Potentiometer Slider

Like the joystick showcased in Figure 3.15, the linear potentiometer input also travels between 1023 points due to the Arduino converting the analog input to 10-bit digital input. These points are mapped to the stepper motor and each point of the linear slider corresponds to a given number of steps traversed by the stepper motor. This is done through the map() function on the Arduino IDE. The function is written as follows.

desiredPos = map(x_pos,0,1023,-90,90)

The 90 in the function represents the steps required to move by the stepper motor. The linear distance that can be traversed by the linear slider is around 55mm. Detailed explanation of the same is continued in testing of the prototype. The linear slider is portrayed in Figure 3.16.

3.3.2 Potentiometer Correction

Input for steering the vehicle is taken from a 10k ohm sliding potentiometer, which converts position of slider to an electronic signal (0-5V) that can be transmitted to the Arduino. This 0-5V analog input is converted into a digital equivalent step between the 0-1023 points of the sliding potentiometer by the Arduino.

During testing, it was identified that the output does not linearly change with the slider position, as it theoretically should. This was creating reduced sensitivity at the extremes, and very high sensitivity at the mean position of the slider. To rectify that, multiple data points were selected, followed by plotting the distance vs. input graph for the potentiometer. The graph turned out to be similar to a sinusoidal curve, heavily deviating from the ideal straight line curve. Figure 3.17 depicts this deviation.

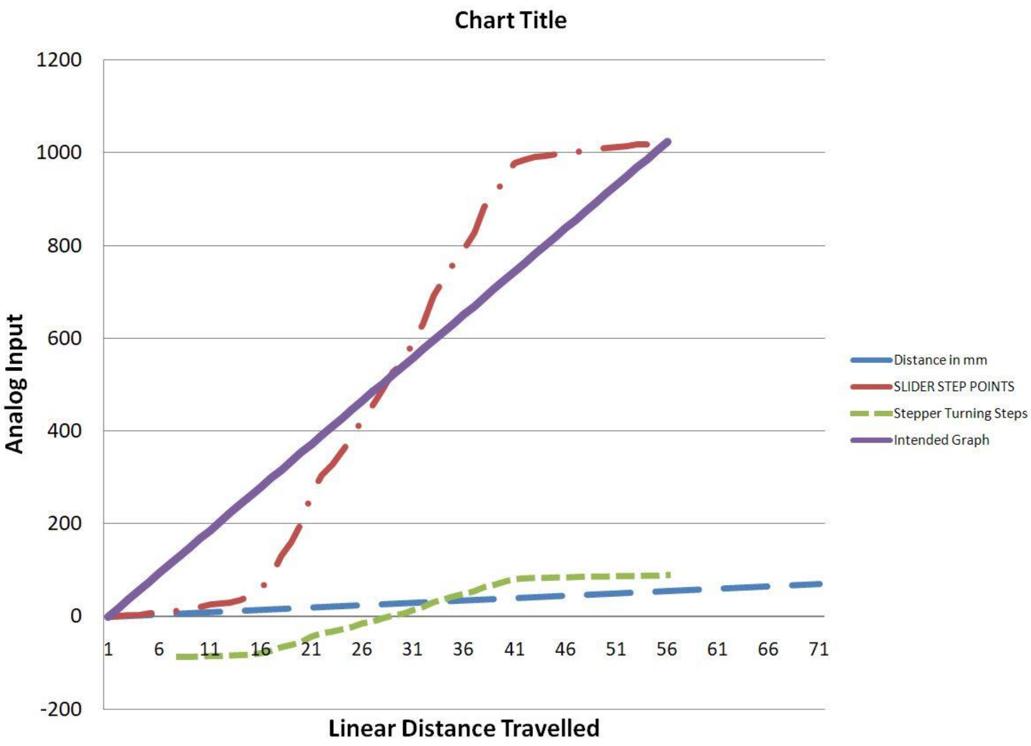


Figure 3.17 Initial Graph Depicting the Plotted Points Of Stepper Turning Steps, Distance Travelled By The Linear Slider And The Slider Points Along With An Ideal Graph

To fix this, a function was added in the code that changed the input and got it closer to the idea line. For this, the slider input is divided into three parts, where Part 1 is from 0 to 60, Part 2 is from 60 to 977 and Part 3 is from 977 to 1023. These values are approximated from the graph above. Then the slope and extent of each Part was mathematically modified to conform to the ideal graph. Figure 3.18 depicts this clearly.

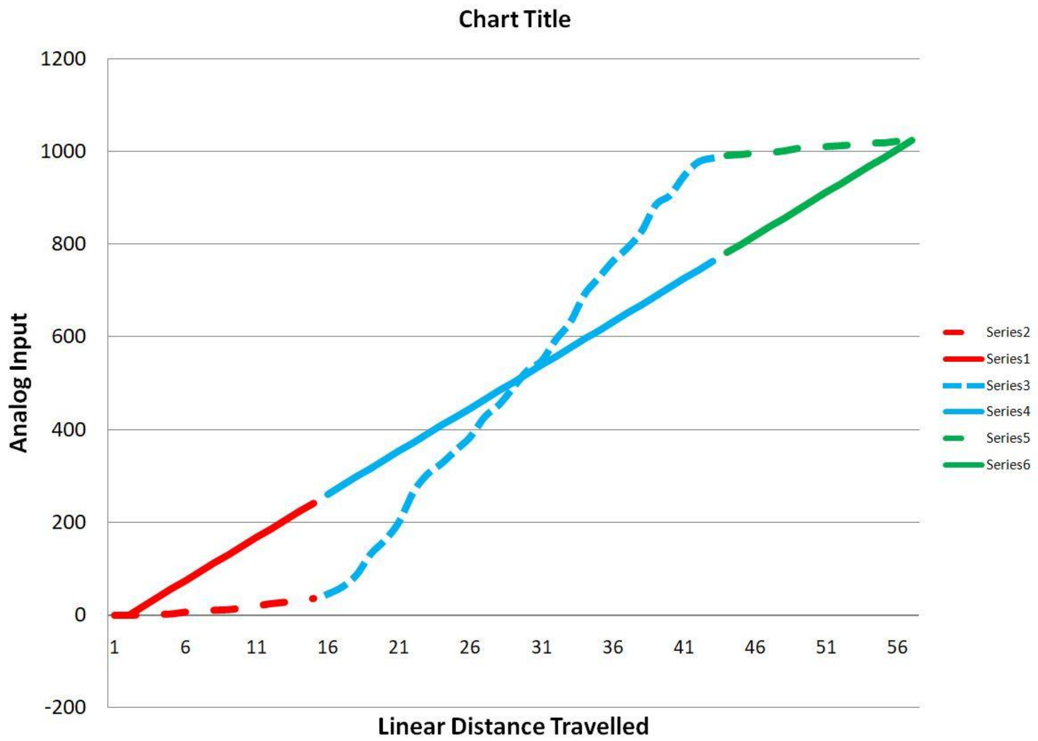


Figure 3.18 Piece-wise Linearization Results with the Transformation

The slider has a linear travel of 55mm. Here, each line segment was converted to the form $y = \left(\frac{55}{1023}\right) f(x)$ to conform to the ideal equation. This equation helps convert the values which don't obey the linear pattern between the slider movement and the potentiometer reading in order to achieve uniform wheel turning during manoeuvring

Part 1:

Actual equation: $y = \left(\frac{15}{60}\right) x$

In new form (reordering the numbers): $y = \left(\frac{55}{1023}\right) * (4.65 * x)$

So correction factor is $4.65 * x$

Part 2:

Actual equation: $y = \frac{x}{36.68} + 13.3642$

In new form (reordering the numbers): $y = \left(\frac{55}{1023}\right) * (0.50708x + 248.5741)$

So correction factor is $0.50708 * x + 248.5741$

Part 3:

Actual Equation: $y = \frac{x}{3.06} - 278.587$

In new form (reordering the numbers): $y = \left(\frac{55}{1023}\right) * (6.0652x - 5181.718)$

So correction factor is $6.0652 * x - 5181.718$

In this way the actual input values were changed to be closer to the ideal linear graph, and the modified values were used later to calculate and actuate front wheel and rear wheel steering.

The following function was added in the Arduino code to bring this change into effect.

```
int CorVal( int z){
  // Function corrects potentiometer output to make it more linear
      int RET;
      if (z<60){
            RET=z*4.65;
            }
      else if (z<977){
           RET=(0.50708*z)+248.5741;
            }
      else{
            RET=(6.0652*z)-5181.718;
            }
      return (RET);
  }
```

An extended version of this and other codes can be found in Appendix 2. This correction helped with the linearity of the potentiometer input. The significance of this can be vividly noticed while the wheels are turned during manoeuvring.

3.4 Hydraulics Design and Development

Hydraulic systems help with force multiplication which is necessary for actuation during steering. This reason is why hydraulic systems are widely used in the industry for actuation and control of pistons, cylinders, robotics end-effectors and high power equipment. In this project, the mechanical and the electronics are accompanied with a hydraulic system that has been developed in order to facilitate the change to zero steer. This project does away with pneumatic systems because of the inherent compressibility of air. This can induce play in the system, thereby affecting the steering capabilities. Hence, in order to change the effective rack length, two hydraulic syringes were attached that can extend up to 50 mm each. 100 mm total extension turns the front wheels in opposite direction, providing the toe-in required for zero wheel steering. The diagram of the entire hydraulic assembly is shows in Figure 3.19.

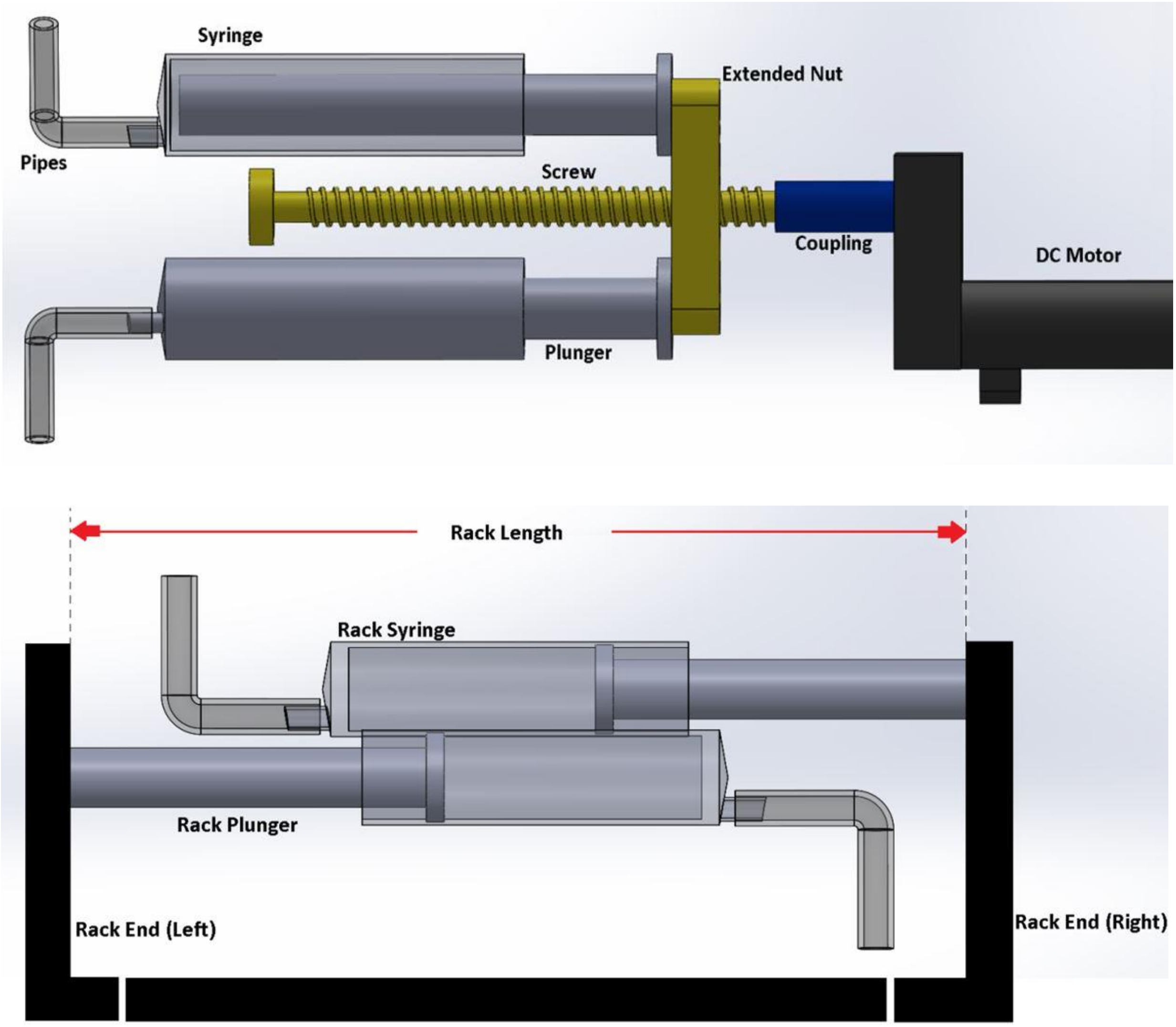


Figure 3.19 Hydraulic Assembly to Actuate the ZTS (a) Control End (b) Rack End

Hydraulic DC Motor

A high torque DC motor is used to provide the necessary torque for the turning motion necessary to actuate the main syringes, and modulate the length of rack syringes. This motor is controlled by the L298N driver which allows running it for a very precise amount of time (Arduino controlled), and also gives the ability to reverse to normal 4WS mode. A 5mm to 5mm coupling was attaches the DC motor to the screw, to transmit the rotating motion. Both the Motor shaft and screw shaft end are 5mm diameter, making this coupling ideal for use. It is secured to both the shafts via a set of grub screws.

The screw is a long, threaded plastic shaft that has a high pitch length. It provides torque multiplication through the difference is speed of rotation. Different from a long bolt, its function is to convert the rotation motion to linear translation motion. It is supported at the free end with a ball bearing, while the other end is coupled to a motor that makes it rotate about its axis. It is in mechanical mate with the extended nut, which is the component that actually translates when the screw rotates.

A standard 5mm ball bearing holds the other end of the screw, allowing it to turn freely with the least amount of friction. The bearing is secured to the wooden base via metallic clamps screwed into the base.

The extended nut is made in combination with the screw, having the same pitch. This makes it a perfect fit for the screw and nut mate, allowing the conversion from rotational motion to turn into linear. This nut, however, has extensions on both sides allowing attachments or guiding rails etc. to be coupled with it. In this case, the main syringe plungers are attached to these extensions to transmit the force to the syringe.

There are two plungers, which convert the linear force into hydraulic pressure by attempting to compress the fluid in the syringes. They are attached to the extended nut (one on each side), and move with it. Using the motor, the motion and directopm can be carefully controlled. The rubber seal on their ends maintain the pressure while transmitting this force to the rack plungers.

Each plunger goes into a syringe, which provides the body to hold the fluid as well as a surface against which the plungers move to pressurize the fluid. They are made from medical grade plastic, and are extremely accurate in measuring the fluid volume in them. The syringes are kept stationary and the pressurized fluid in them can only escape one way, the pipes. Fluid transmitting pipes are attached to each syringe, connecting them with the rack syringes. They are the means to transmit the fluid (and with it, the power) to the rack end of the assembly, permitting to change the length at will. These 5mm pipes as pneumatic lines are chosen for their strength, resistance to deformation and an extreme ability to withstand pressures as high as 5-10 bar. The fluid acts as the force transmitting medium, by uniformly distributing the pressure, causing force transmission and multiplication with very little losses. The fluid chosen here is water, due to its easy availability and high Bulk modulus (resistance to volumetric compression).

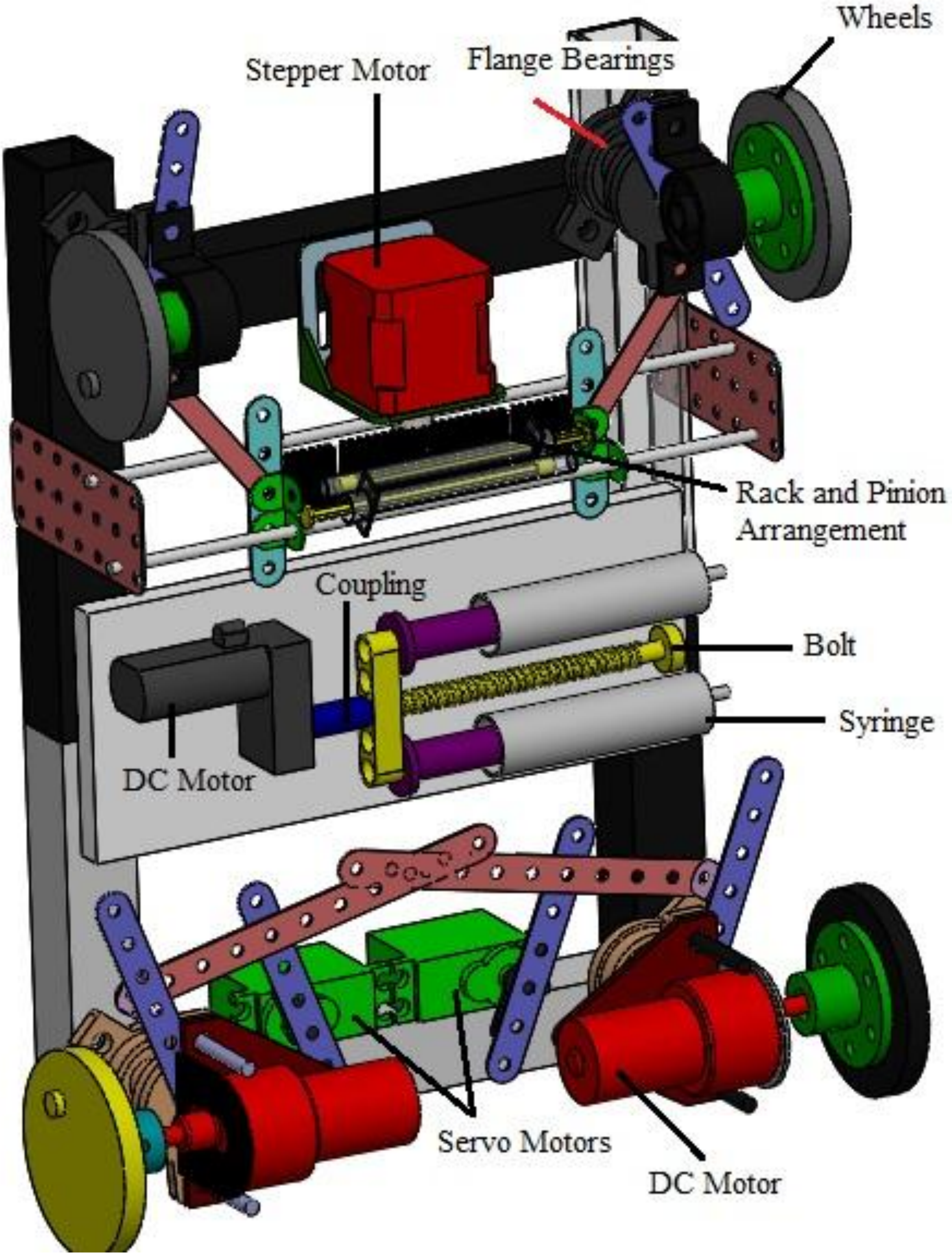


Figure 3.20 CAD Displaying The Underside Of The Prototype

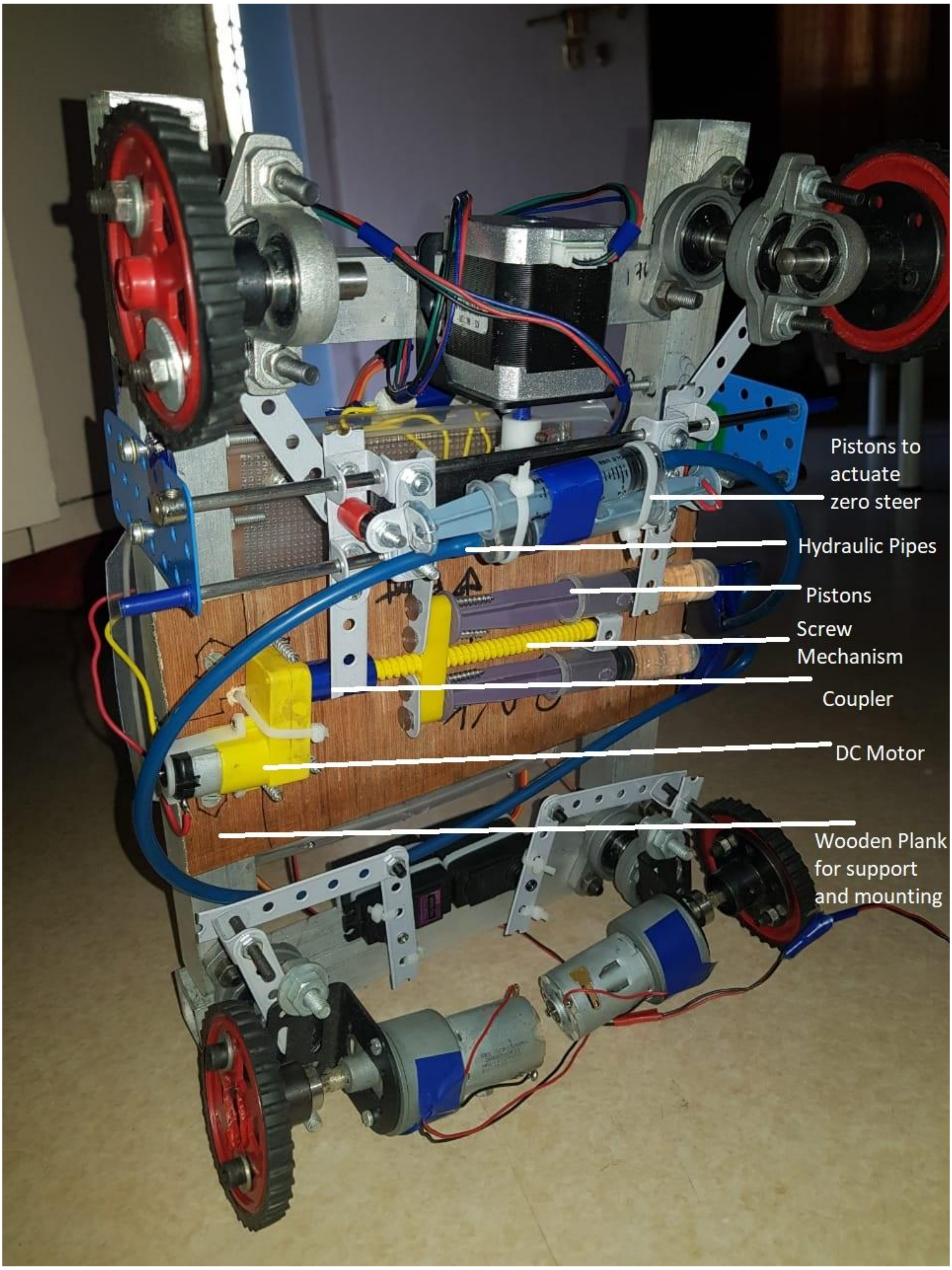


Figure 3.21 Underside of the prototype showcasing the Hydraulic Assembly

Two pipes (one from each main syringe) connects into the pair of syringes that are kept above the sliding rack in the front of the vehicle. The pair of syringes on the rack end are attached to one other, to prevent relative motion. The fluid pressure that fills the syringes is applied on the plungers, allowing modifying the distance between them. These syringes are fixed in a way as to not flex or bend, thus all the motion is utilized in increasing/decreasing rack length.

Finally the fluid pressure acts on the rack plungers, which move proportional to the distance moved by the plungers of the main syringe. Since the fluid is ideally a closed loop, their motion can be controlled very precisely by controlling the motion of the main cylinder plungers. The ends of these plungers are connected to the left and right free ends of the rack. As their outer syringe body is fixed, any increase in length pushes the rack ends apart, giving the rack extension as and when it is needed.

The underside of the CAD of the vehicle is shown in the Figure 3.20. Further, Figure 3.21 shows the entire assembly of the vehicle.

3.5 Complete Prototype Design

An advantage of the build idea pursued here is a combination of mechanical and electronic ends. The project could be replicated as a complete mechanical or a complete electronic build. The complete electronic build is a more favourable design because of its relative simplicity and wider range of applications. The build is shown in Figure 3.22 and the remote is shown in Figure 3.24. Figure 3.25. shows the complete electronics layout.

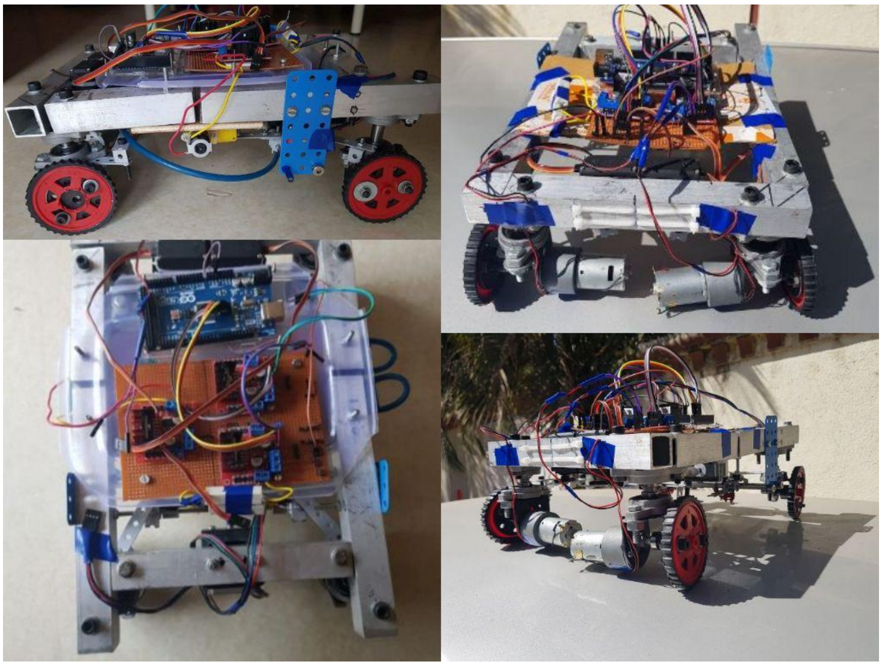


Figure 3.22 Complete Build Clockwise: From Top Left: Side View, Front View, Front Three-Quarter View, Top View

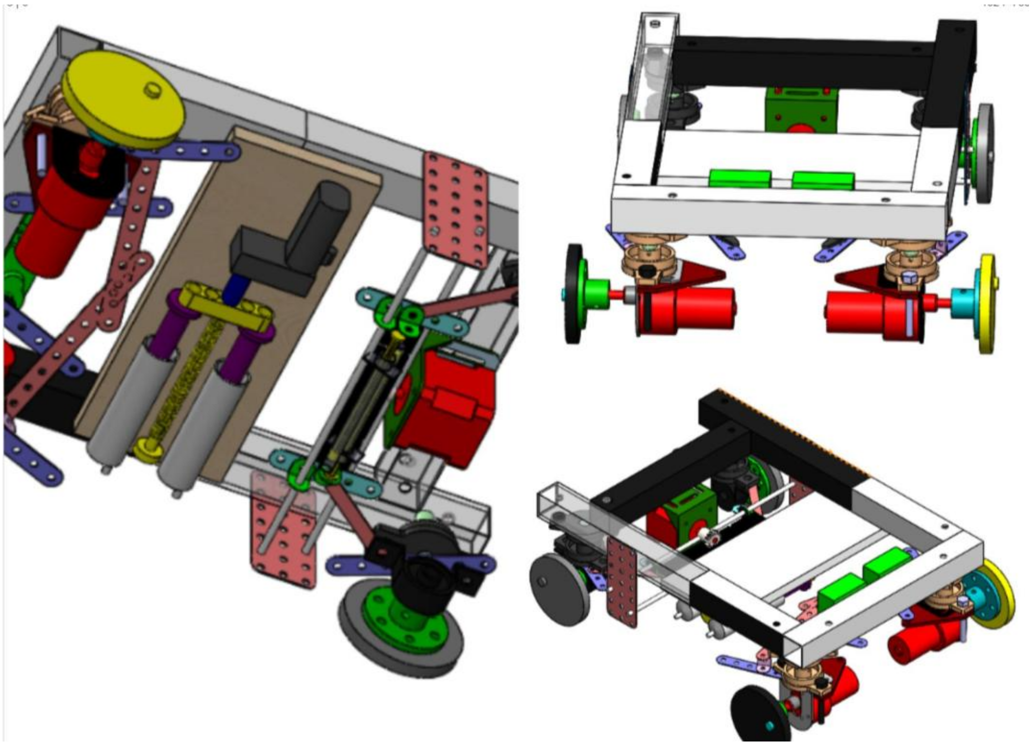


Figure 3.23 Complete CAD. Clockwise: From Top: Bottom View, Side View, Top Three-Quarter View

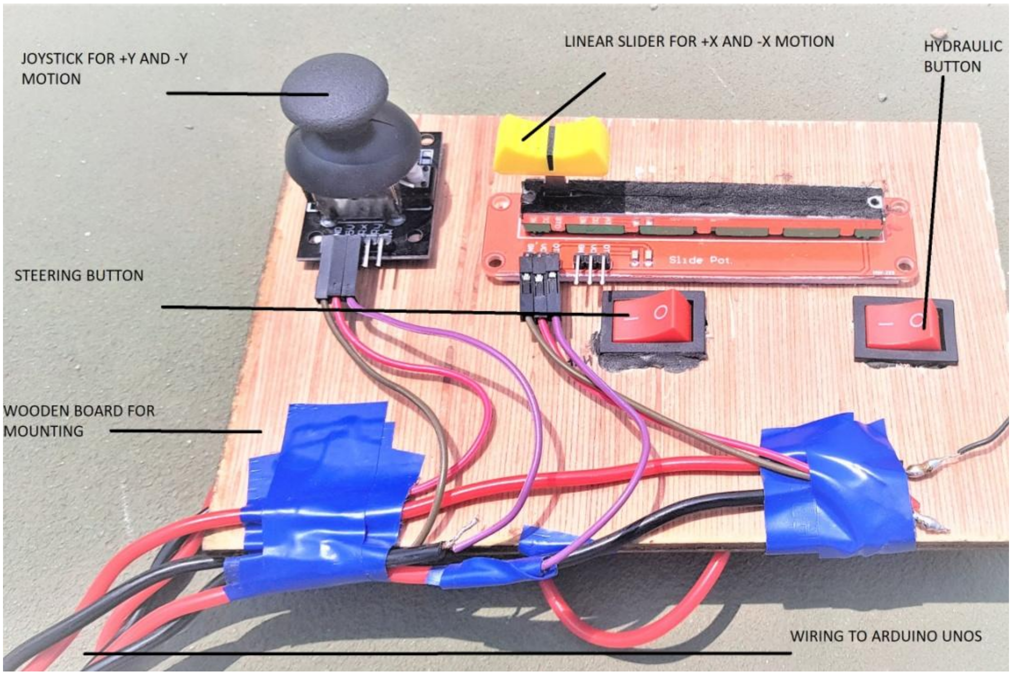


Figure 3.24 Remote for Control with Assembled Potentiometers and Buttons

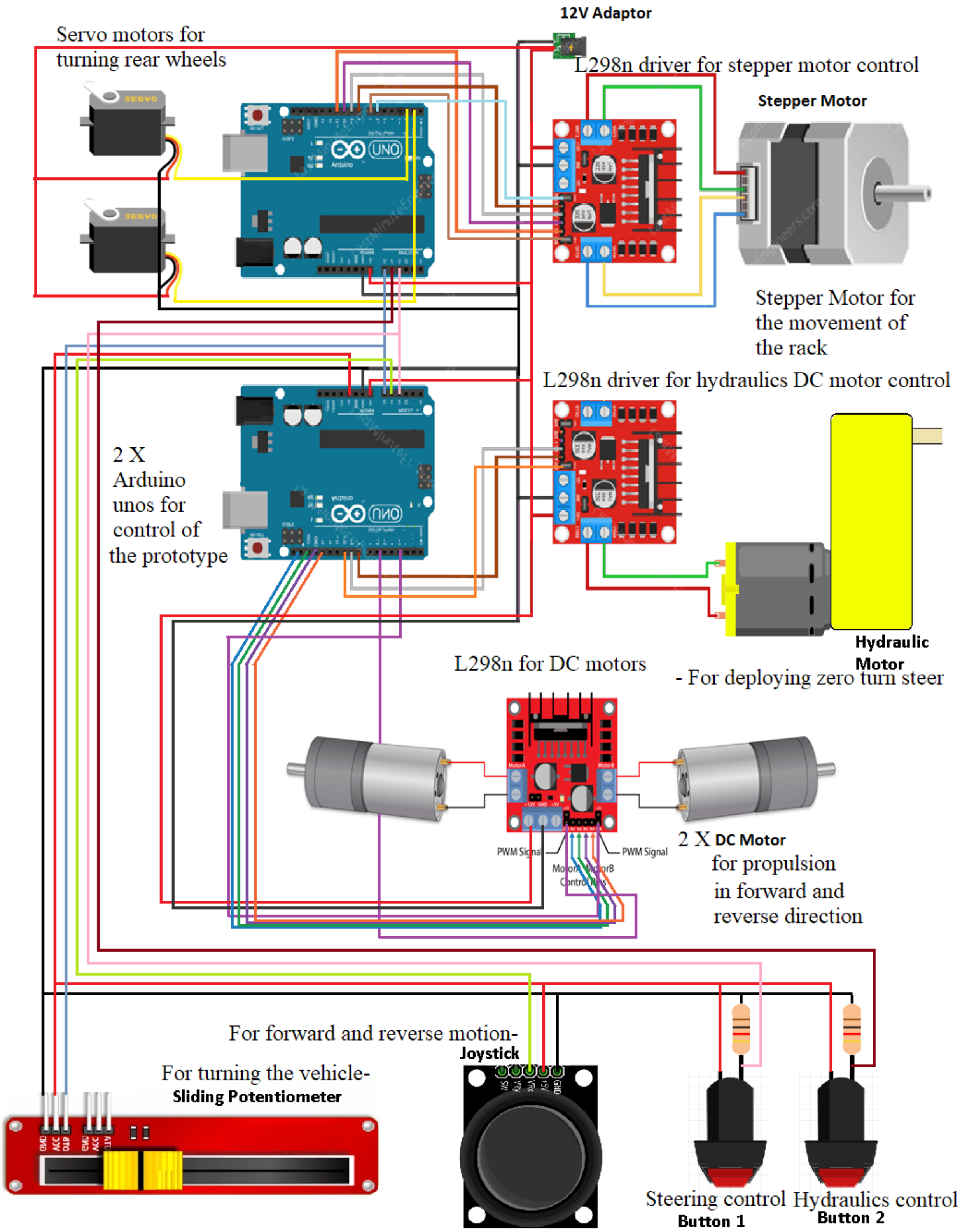


Figure 3.25 Complete Electric Circuit for Prototype Operation

3.6 DFMEA of Steering System

The DFMEA is a necessary tool in order to detect any potential faults that could hamper the smooth functioning of the steering system. In general, DFMEA is an ongoing process during the entire design stages of the product. It further helps with countering product malfunctions. This DFMEA explores the various systems and sub-systems our model has, and the functions each of them perform. For each component, every failure mode is identified by looking at various ways in which its function can be compromised. As this is a Design Failure Mode Analysis, only failure modes related to the design phase of the model are listed. They cover various design considerations and assumptions, empirical methods adapted to arrive at design data, reliability of simulation results, prototype testing and the impact of Factor of Safety. For each failure mode, alternate and more robust design criteria are then suggested, which attempt to reduce the occurrence, severity and detection rating of the said failure mode. In this way DFMEA offers a chance to find potential faults in the design process, and rectify them. Table 3.3 shows the DFMEA of the Steering System.

3.7 DVP of Steering System

The Design Validation Plan was designed to test that components we selected worked as per our expectations individually and as part of a subsystem and as a whole when fit on the prototype. Major components like DC motors, Stepper motor and the Servo motors were tested separately to ensure it functioned as mentioned on the specification sheet. Additionally, each subsystem namely the two rear assemblies, the front assembly, and the hydraulic system were tested separately for speed, accuracy and synchronization. The structural members were also tested for their rigidity under reasonably assumed loading condition. These tests have proved to be insightful and have, in some cases led to the modification of the design in order to better suit our needs. Tests performed on all units/subsystems have been satisfactorily passed. Table 3.4 shows the DFMEA of the Steering System.

3.8 Conclusion

This section detailed the complete build of the vehicle and the assembly. The prototype was a wide variety of mechanical, electronic and hydraulic systems all working in unison in order to actuate the wheels as per the user request for various driving modes. This section also highlighted the reason behind some decisions made during the design and assembly phase throughout the duration of the project.

Chapter 4 Specific Low Speed Applications

4.1 Introduction

The scope of this project extends towards various industries. The breadth of abilities is only limited by the technical and economical feasibility of the design and assembly of the project. Some of the major applications of this project can be:

- Varied warehouse applications
- In-house wheel chair manoeuvrability
- Low speed robots
- Agriculture
- Construction
- Unmanned vehicles for military and off-road applications
- All Terrain Vehicles (ATV)

While a plethora of applications are listed here, one of the most useful applications of this type of zero turn steer can be found on wheel chairs for the handicapped for indoor as well as outdoor applications.

4.2 Wheel Chair Design and Requirements

Traditional wheel chairs are limited by its design. While these can be folded and stowed away in tight spaces, they can't be of much use to turn around in every tight corner of a room. To get around this issue, a change is proposed in steering design for the same.

Figure 4.1. shows a study published by Stanford University [31], which shows the space needed for a U-turn by a wheel chair .

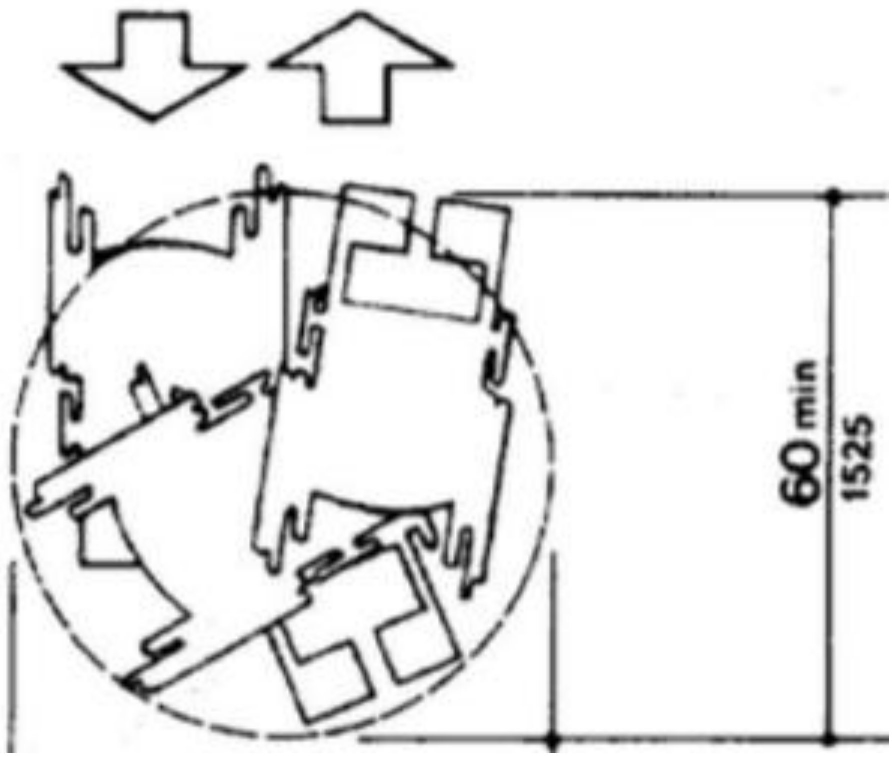


Figure 4.1 Prescribed Turning Circle (60in or 1525mm) for a Wheel Chair **[31]**

The Figure 4.2 above was selected from a study published by researchers at Stanford University. This shows the inherent drawbacks in attempting to take a turn at a dead end using a conventional wheelchair. These include an increased turning circle radius and an added difficulty for the user that naturally comes with it.

Figure 4.2 indicates the space needed to negotiate a 180 degree turn at a T-space using a conventional wheel chair. In contrast the wheelchair with a zero turn steering system can counter these downfalls with its improved steering characteristics.

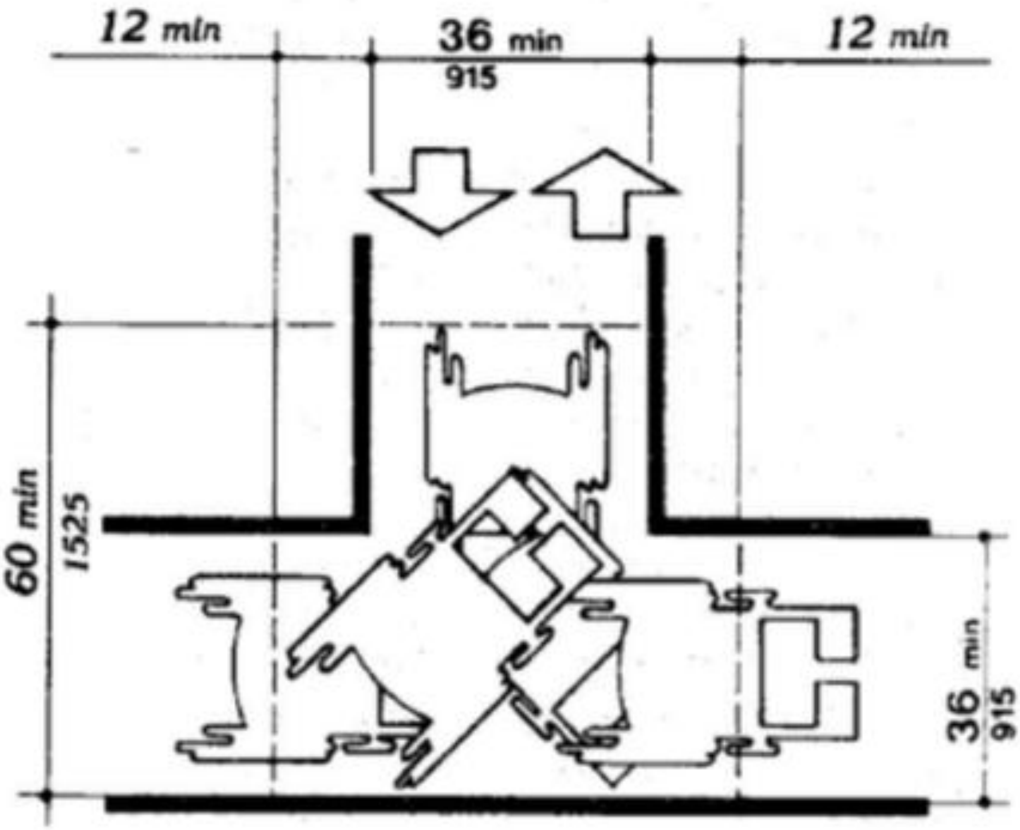


Figure 4.2 The prescribed T-Space for a 180 Degree Turn of a Conventional Wheel Chair **[31]**

With this system, albeit with necessary modifications will close to nullify the turning circle radius of the wheelchair and can allow the person to turn about its own axis as depicted here. Figure 4.4 and Figure 4.3 shows a depiction of how a turn would look like on a proposed modified wheel chair system.

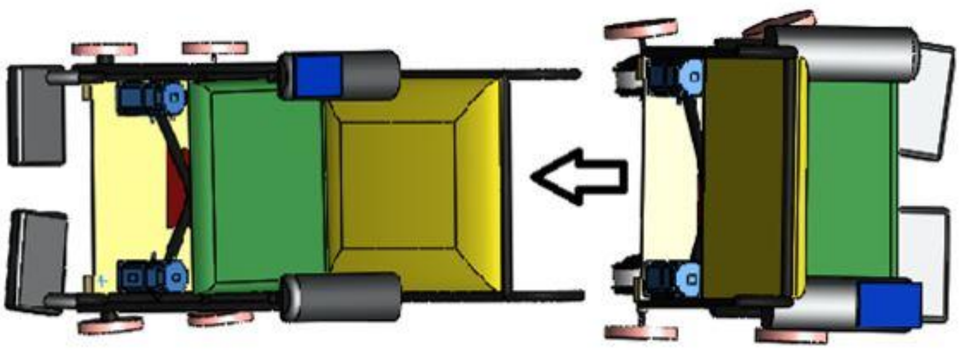


Figure 4.3 Zero Turn Steer on a Modified Wheel Chair

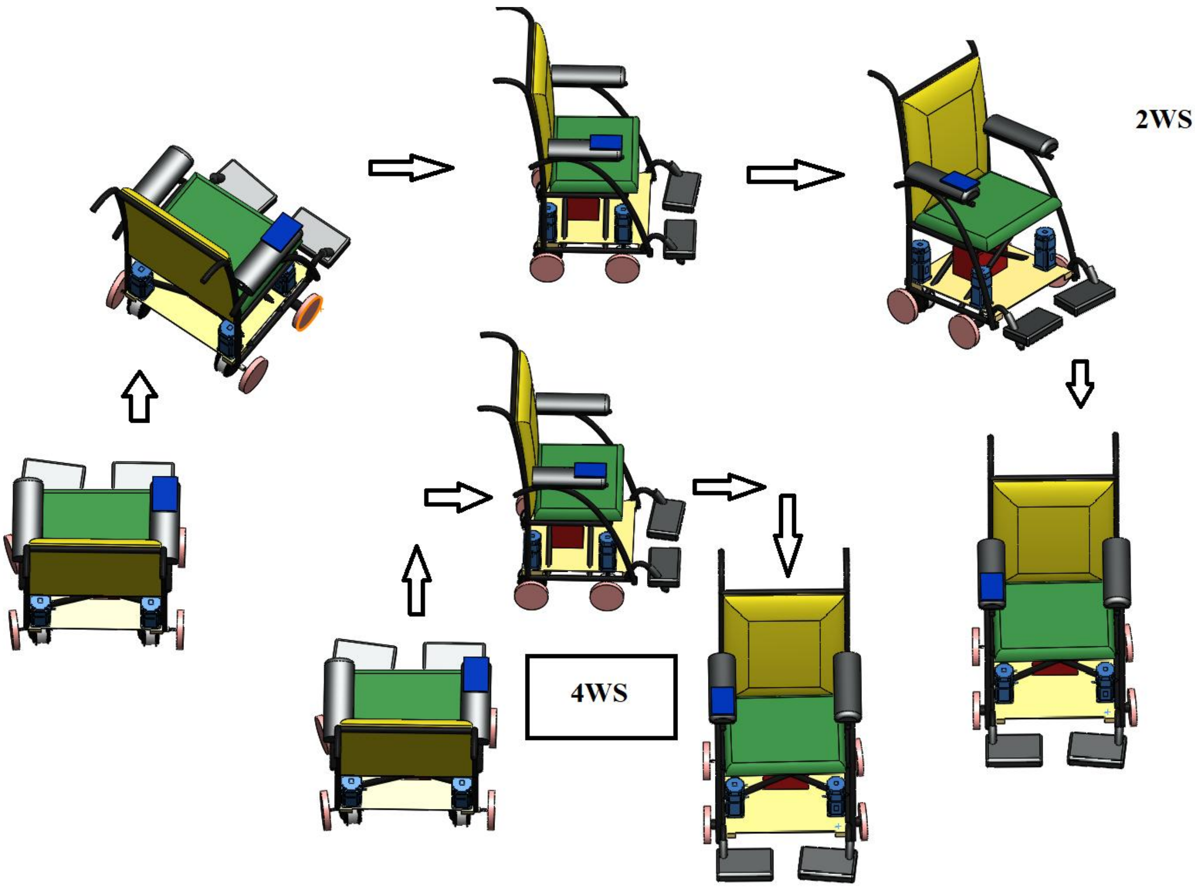


Figure 4.4 2WS vs. 4WS for a Modified Wheelchair

Here Figure 4.4 shows the difference in turning circle radius between a wheelchair occupied with 2WS and 4WS modes. Additionally, Figure 4.3 represents a wheelchair executing zero turn steer. This shows the extent to which the benefits are present in this system.

4.3 Calculations for Wheel Chair

In the calculations below, the load, battery weight, average weight of wheel chair and the weight of the electric motors is estimated.

Using this, the total power that would be required to propel the wheel chair forward. Table 4.1 shows the estimates.

Table 4.1 Estimates of Wheelchair Weight (Consult Appendix 7 for more)

Assumed load	178kg (99th percentile of weight)
Battery pack weight (24V Li-ion battery pack 11000mAh, 30X Li-ion 3.7V 2200mAh cells)	1.5 Kg
Weight of the chair frame	35 Kg
Raw frame weight	35 Kg
Total weight of all motors	23.8kg
500W 24V DC motor weight	4.30 Kg
87 kg-cm Hybrid Stepper Motor weight	3.62 Kg
4*Stepper-motor weight + 2*DC motor weight	38kg
Estimated total weight after addition of auxiliary components (cushions, bearings, fixtures, leg rest, arm rest, handles etc)	240 kg.

Frame is of cylindrical section, with total length about 10 m (from design CAD MODEL). Coupled with the known density of mild steel, the raw frame weight is calculated to be about 35 Kg. Calculating the power assuming a suitable value for the coefficient of friction and a desired speed, the total power required from the electric motors is calculated.

Total Power Requirement:

Coefficient of friction – 0.4 (typical value for home tile)

Weight – 240 kg

Peak speed – 8 Kmph (standard speed for electric wheelchairs like CosmoCare Automate or Vissco Ziplite) [32]

Hence, evaluating the total power:

P= F.v = 1.5516 kW = 4.1 hp

Hence, the wheel chair would require a power of about 2.1 hp per motor to propel itself.

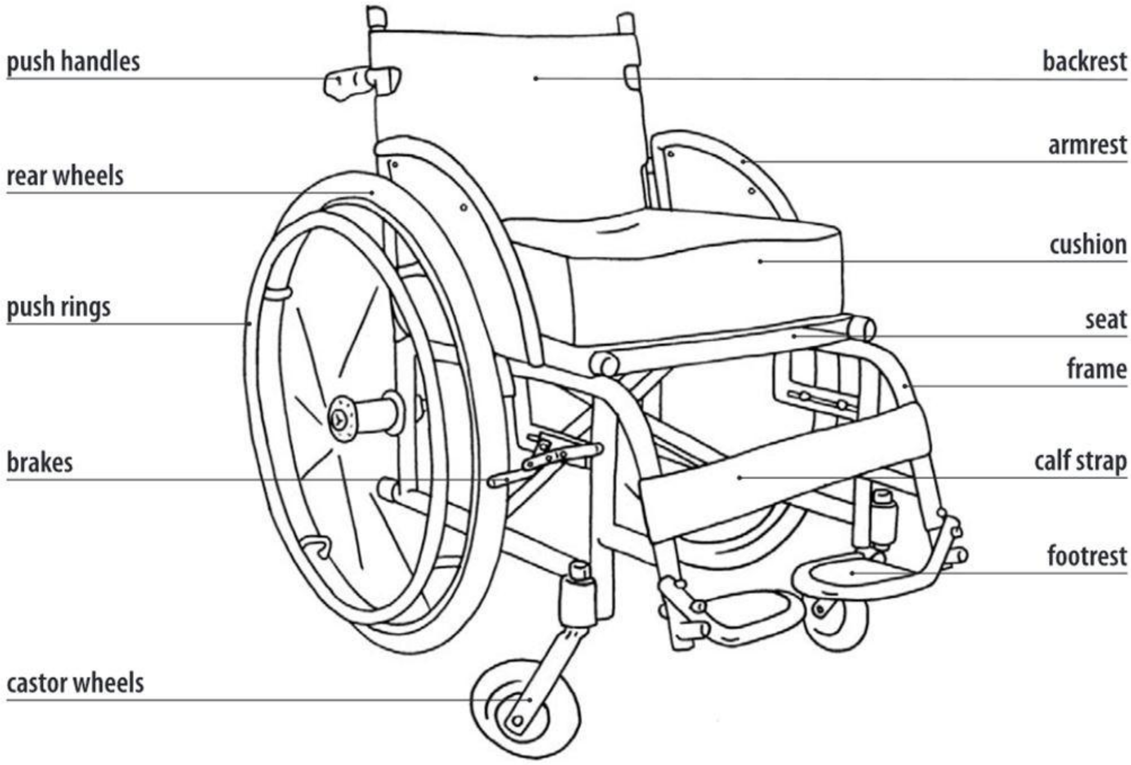


Figure 4.5 Wheelchair Parts

Apart from the electrical specifications, there are other mechanical considerations while designing a wheelchair. Some of them are given in Table 4.1.

Footrest: Footrest should fold with a reasonable amount of force. It should not break or bend when used to lift user and wheelchair. Additionally, it should not break or bend when additional passengers or packages are loaded. Also, it should not break or bend when hitting an object such as a wall or curb.

Brake: Brakes should stop a wheelchair from sliding when on an incline. Brakes should not suddenly release while in use.

Armrest: Armrest should be removable with a reasonable amount of force. It should not break or bend under the user's body weight. The armrest should not break or bend when used to lift user and wheelchair.

Push handles: Push handles should not break or bend when used to lift user and wheelchair. Handgrip should not slide off of push handle when user is being assisted up stairs or curb.

Frame: Frame should not break or bend when used on uneven terrain.

Backrest and seat: Backrest, seat and frame should not break or bend during transfer or while riding on uneven terrain.

Rear wheel and axle: Frame, wheels or axles should not break or bend when user goes over a normal curb.

Wheels, axles or wheel-mounting hardware should not fail when user drops off curb at angle. Axles or wheel-mounting hardware should not break or bend when under typical forces.

Castor assembly: Castor should not fail when the castor wheel hits an object (e.g. a curb).

General points: Surfaces should not have sharp edges, sharp points or pinch points. Wheelchair should not be flammable, i.e. easily combustible materials should not be used. Additionally, the wheelchairs should be equipped with front and rear reflecting stickers or signs for increased road safety.

Tipping levers should not break when assistant uses levers to tip user back. Hand rim should not break or bend when it hits an object. Wheelchair should not break when it falls or is dropped by handler loading or unloading it from bus or car. Considering the above mentioned points, a prototype of an electric wheelchair was designed on SolidWorks 2016 and stress analysis was conducted on ANSYS 16.2.

4.4 Wheel Chair Prototype

Having designed a prototype template that can be used in various applications of construction, agriculture and medicinal industry, a decision was made to go further and design a prototype of a wheel chair and depict how this system can be implemented. Just like the prototype created above, selection of the frame for the wheelchair has to take the motion of the motors into consideration. The build has been clearly depicted in Figure 4.6 through to Figure 4.10. The battery is selected based on the requirement of wheelchair range of 15km. The battery is a 24V Li-ion pack with 11000mAh current capacity.

Further MATLAB and ANSYS simulations were conducted on the wheel chair to test the design of the build. The factor of safety was also measured and mentioned after the simulation.

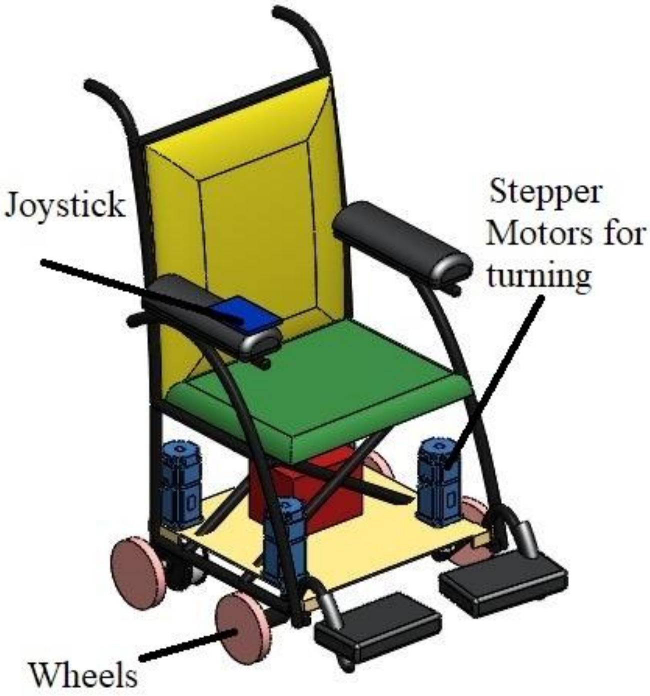


Figure 4.6 Proposed Wheelchair Design

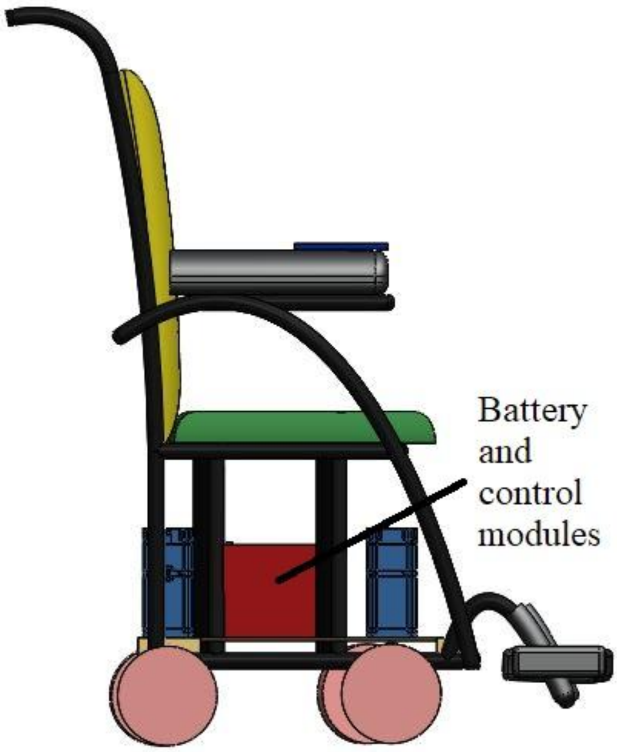


Figure 4.7 Packaging of Battery and Control Modules on the Wheelchair

Figure 4.8 Rear End of the Wheelchair

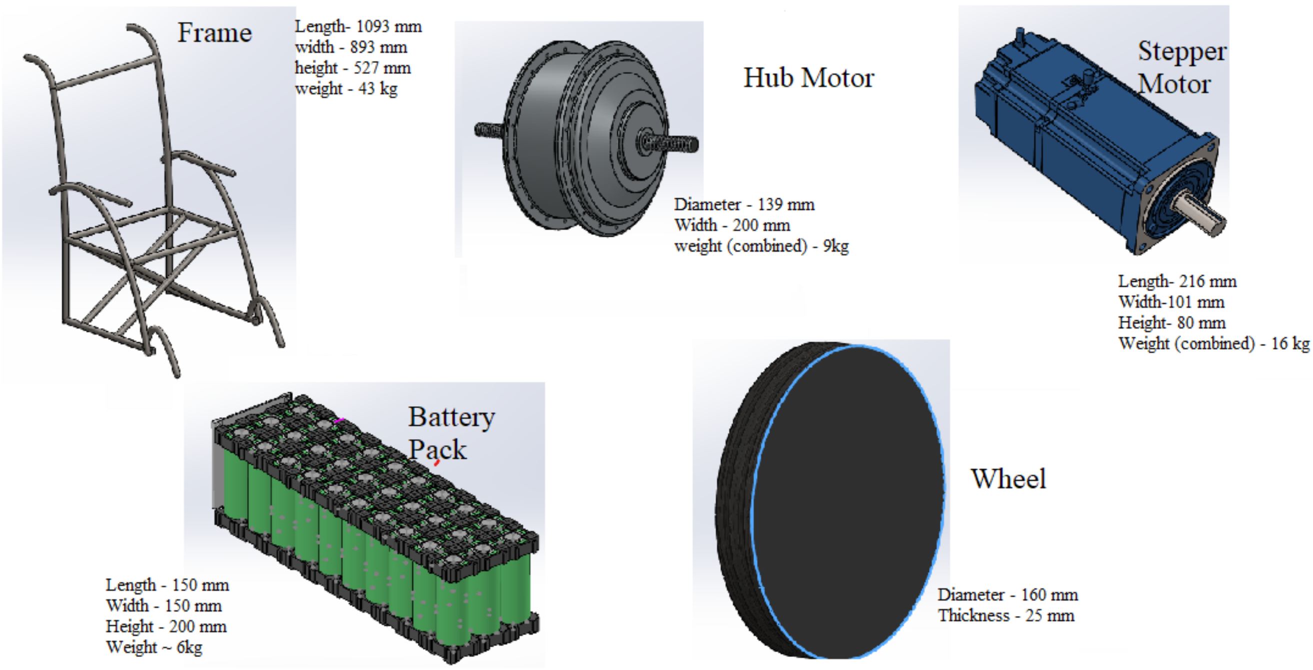


Figure 4.9 Individual Parts of the Electric Wheelchair Prototype

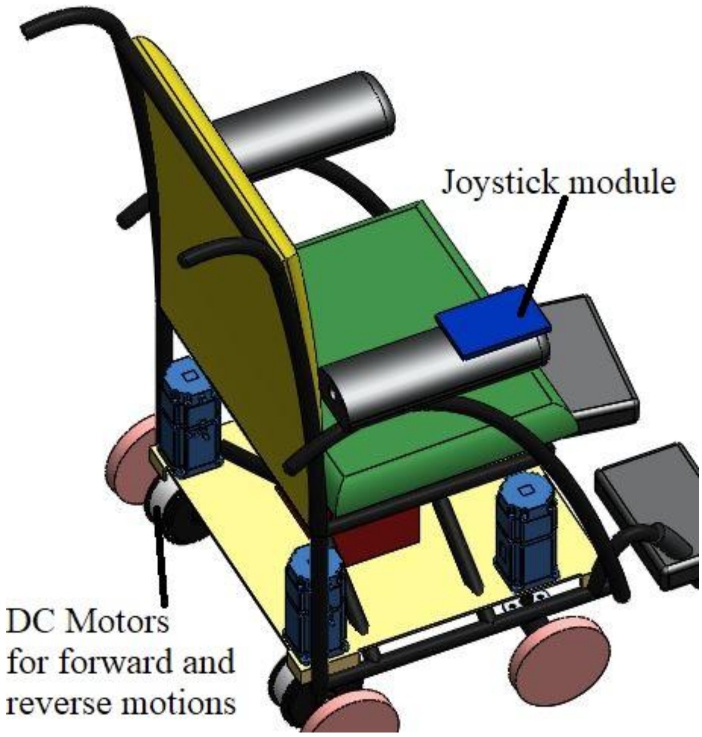


Figure 4.10 DC Motors and Joystick Module on the Wheelchair

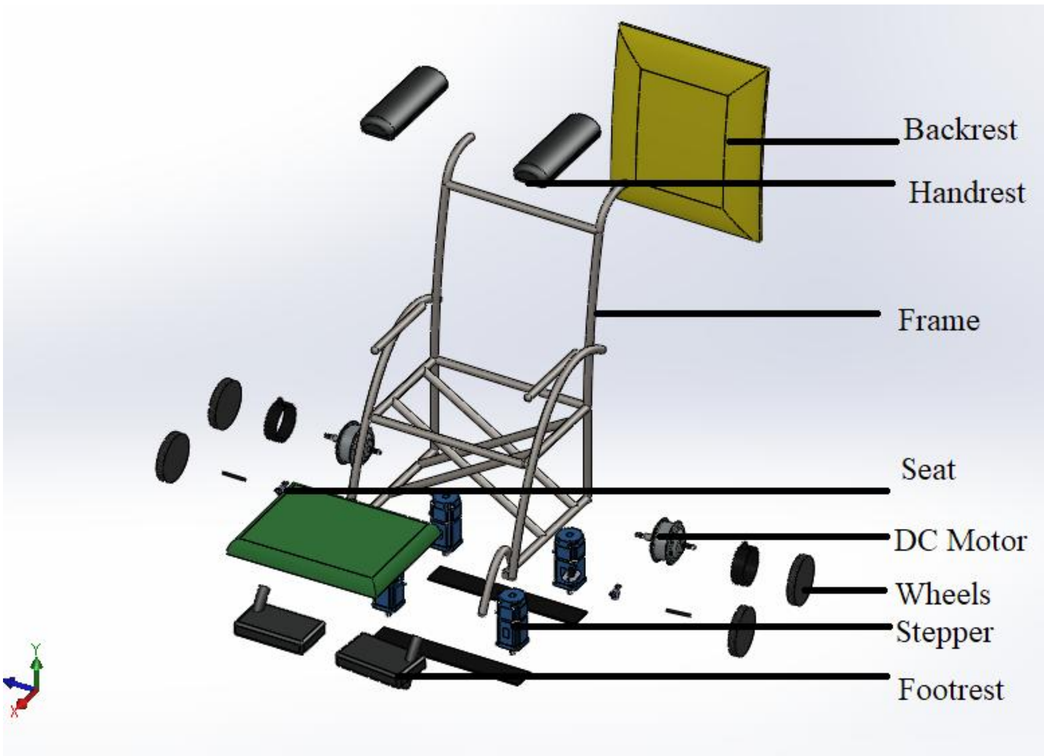


Figure 4.11 Exploded View of the Wheel Chair CAD Model

Sufficient space has to be provided to allow for swivelling of the motors, as well as to prevent their collision with the micro-controller and the battery assembly. The prototype has hub motors in the wheels which can be used for propulsion. This is aided by 4 Stepper motors that can be used for turning the wheels. Of course, these stepper motors just serve as a template. Any stepper could be used depending on the specific use and load propulsion requirements. Since the rear wheels need to steer the big wheels are eliminated, ubiquitous in conventional wheel chairs.Instead, the prototype designed here has smaller wheels that can help with steering and forward motion as well.

The prototype is also occupied with a battery pack that is mounted at the underside of the wheel chair. It is also occupied with a charger port that can be plugged into the grid in order to recharge the wheel chair for use when necessary. Provisions should also be given for the motors to be mounted without falsely taking the load applied by the user. Having the wheels inbound can be of added advantage in order to prevent dangerous accidents with loose elements belonging to the user or the environment.

4.5 Wheel Chair Simulation on ANSYS 16.2

Frame for the wheelchair was designed using 25mm thick solid pipes due to their ease of availability. Trusses were added to keep the weight the weight low while adding re-enforcement to make the structure rigid.

Simulation was performed on ANSYS Workbench 16.2 under the static structural module. The CAD MODEL for the frame was designed on SolidWorks 2016 and imported to ANSYS. The auto mesh feature was used to mesh the geometry. With curvature relevance set to 50%, high smoothing, slow transition and span angle centre set to fine. A vertical load of 250 kg, which was estimated in the previous section, was applied over the frame members that support the seat to simulate an excessively obese individual.

Fixed supports were given at the base of the frame where the wheels would be attached The Results of the Simulation show that the frame has a healthy safety factor of 2.017 (generally > 1.5 is deemed acceptable) under these extreme loading conditions.

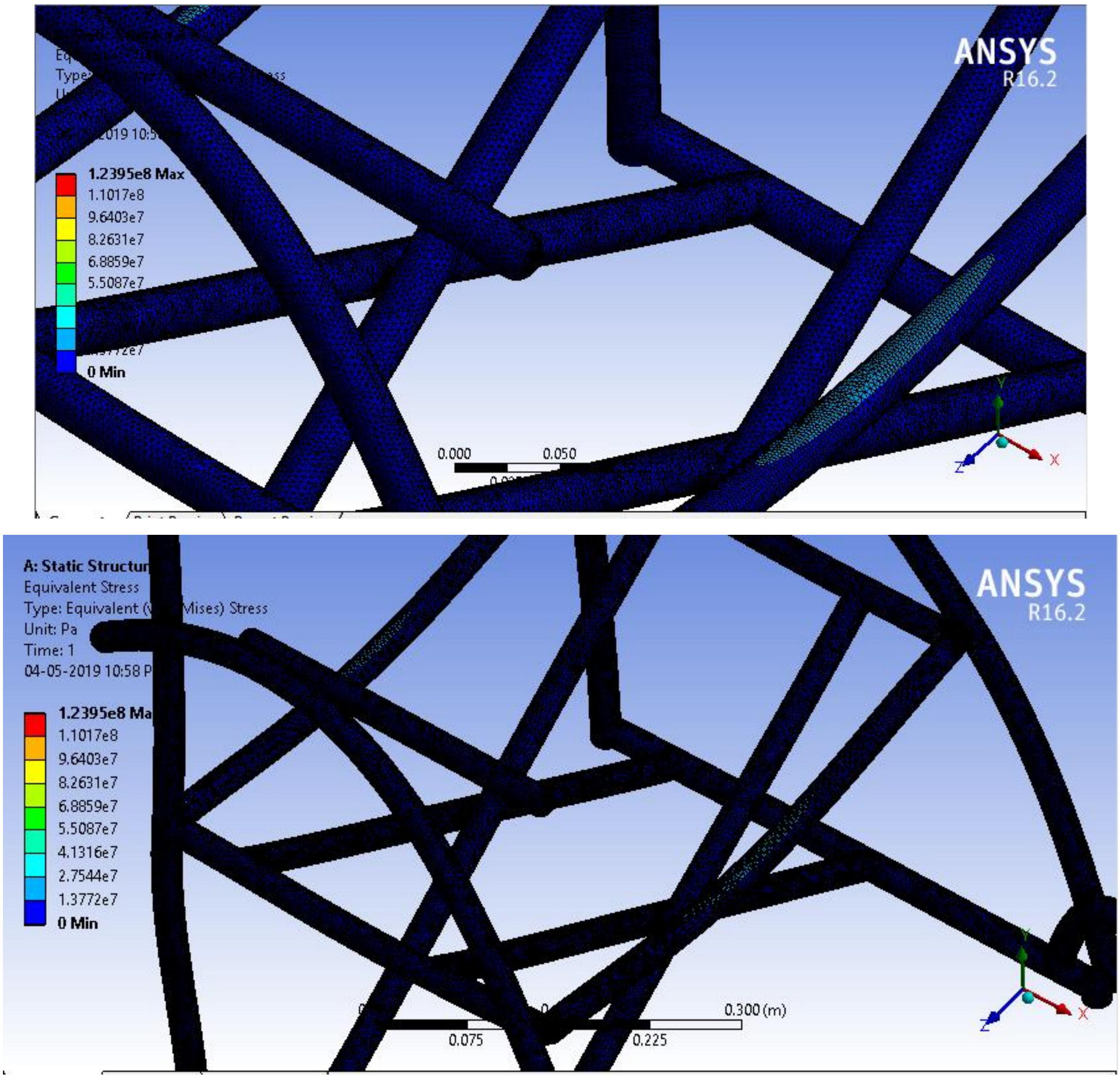


Figure 4.12 Structural Simulation on Frame Members (a) Highlighted Stress Areas (b) Wide Field of View

4.6 Wheel Chair Simulation on MATLAB

The design of the wheelchair would be different from the prototype in the following ways.

1) Weight carrying capacity.

2) Exclusion of rack and pinion and the hydraulic system to be replaced with two stepper motors for independent angle control of the wheels.

3) Inclusion of a battery pack within the system.

4) Wheel hub motors replace the Brushed DC motors in order to enable steering of the powered wheels as well.

The wheelchair would look like a traditional electrical chair with the addition of a compartment below the chair that would house the power electronics and the Stepper motors

In MATLAB, a 260mm chair was selected and the TCR was simulated. It was observed that for 2WS a TCR of 581.377 mm was observed. However, by deploying 4WS it is observed that a TCR of 412.227 mm. This reduction validates the very concept of 2WS. Please refer to Figure 4.13 for same.

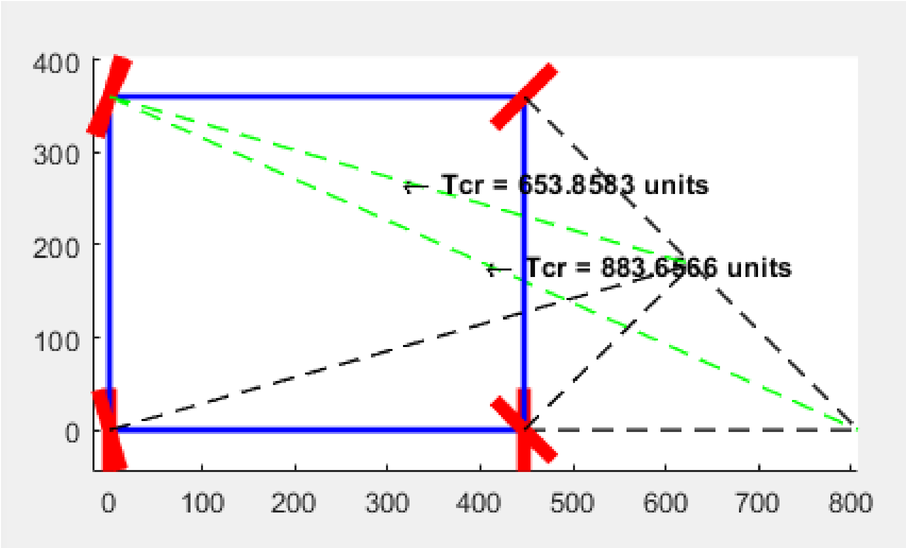


Figure 4.13 MATLAB Simulation Results for the Wheelchair

4.7 Conclusion

The prototype that has been developed in a representation of te possibilities with this steering systems. The CAD model can be tailored for specific uses and can be made as per the application. Our proposed design has quad motors for direction change in order to help with simplicity of design and build.

Chapter 5 Testing and Results

5.1 Introduction

Thorough testing was conducted on the prototype in order to calculate the TCR of the working model. For the prototype to be of superior characteristics, the project was aimed at having a percentage reduction of at least 20%. All the results have been tabulated and have been laid out clearly below.

5.2 Turning Circle Radius Determination

5.2.1 Method of Testing

In the testing phase, a reservoir was positioned to drip water onto the wheels which then traced the path around a circle for each value of the angle turned by the wheels. The test was conducted for 2WS as well as 4WS.

Due to hardware limitation such as servo minimum angle movement and stepper response angle in the code, measurements were made for a minimum for 5 degree steps. These values include 20, 25, 30, 35, 40 and 45 degree. 45 degree is the maximum turning limited by the geometry. Table 5.1. shows the values obtained.

Table 5.1 Raw Testing Data for 2WS and 4WS

Inner Wheel Angle (degrees)	Outer wheel angle (degrees)	TCR for 2WS (cm)	TCR for 4WS (cm)
45	23	75.29	38.32
40	22	111.30	45.94
35	20	129.10	51.67
30	18	131.28	53.30
25	16	172.30	62.35
20	14	186.31	83.62

The values were plotted and a trend line was obtained, which was then plotted to a third degree polynomial. These graphs are plotted as shown in Figure 5.1 and Figure 5.2. This polynomial offers a chance to interpolate the values in between which further helps to understand the TCR reductions throughout the range.

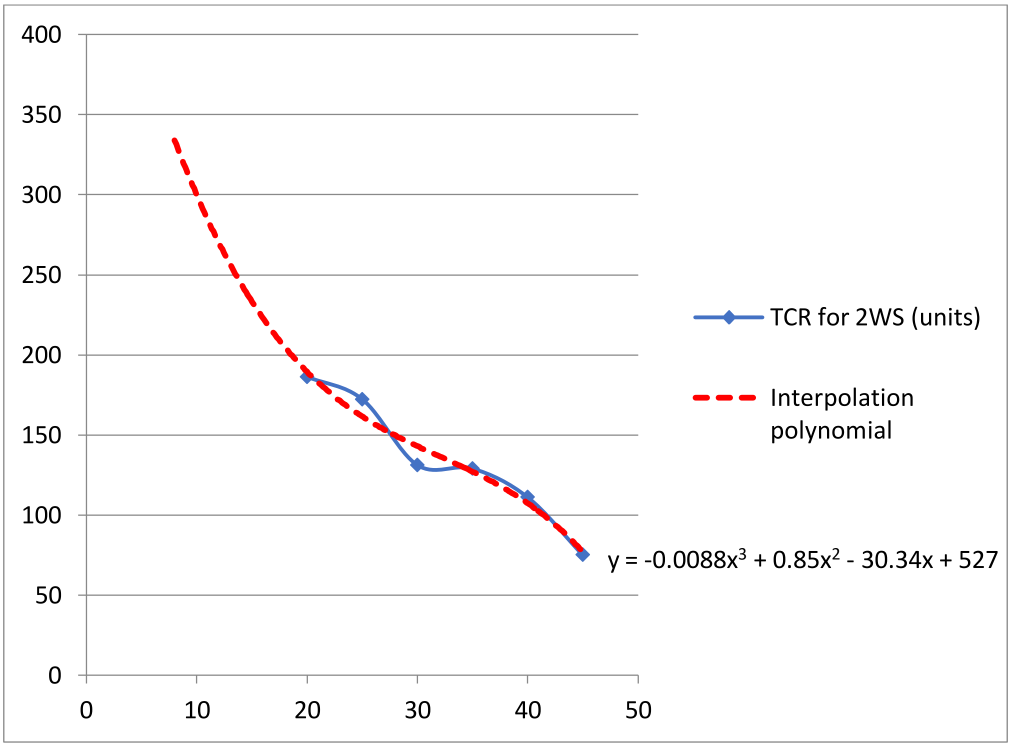


Figure 5.1 2WS Data Interpolation from Raw Testing Data

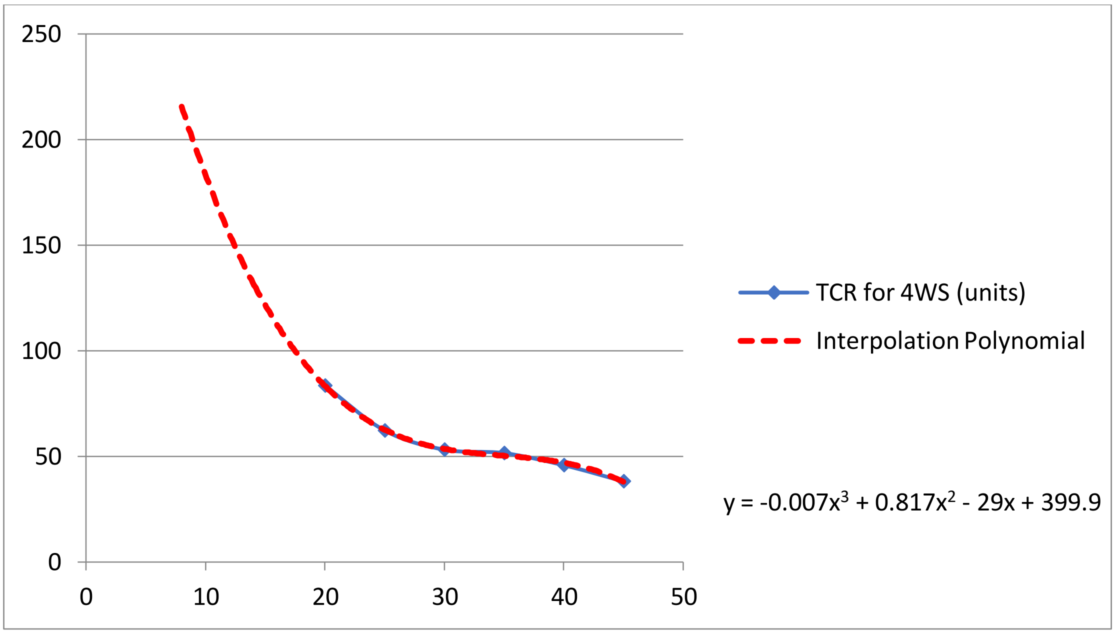


Figure 5.2 4WS Data Interpolation from Raw Testing Data

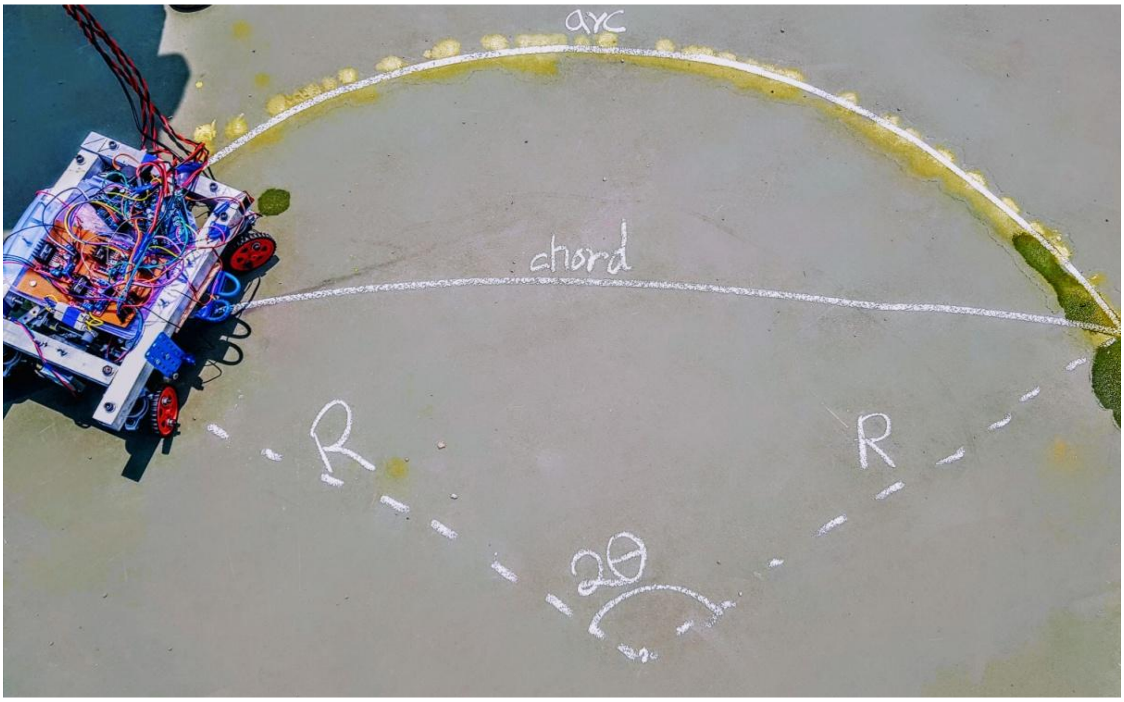


Figure 5.3 Testing Procedure for TCR Measurement

The vehicle was attached with a reservoir to drip water onto the tyres, which can further trace a path as desired. Due to large values of the radius, it's a better option to trace an arc and measure the chord. The above two values are recorded and the radius of the circle is calculated from the arc length (l) and the length of the chord (c). Figure 5.3 shows the dotted arc as the path traversed by the prototype vehicle.

Table 5.2 Final TCR Reduction Data

S. No	Inner Angle (degree)	Outer Angle (Degree)	2W- TCR (mm)	4W-TCR (mm)	Experimental % reduction
1	45	23	752.90	383.20	**49.10**
2	44	23	880.20	405.82	53.89
3	43	23	943.60	427.07	54.74
4	42	22	1001.40	444.82	55.58
5	41	22	1054.05	459.29	56.43
6	40	22	1113.20	459.40	58.73
7	39	21	1145.82	480.29	58.08
8	38	21	1186.06	487.75	58.88
9	37	21	1223.23	493.81	59.63
10	36	20	1257.87	498.90	60.34
11	35	20	1291.10	516.70	59.98
12	34	20	1321.64	508.22	61.55
13	33	19	1351.84	513.32	62.03
14	32	19	1381.61	519.36	62.41
15	31	18	1411.49	526.80	62.68
16	30	18	1312.80	533.00	59.40
17	29	18	1473.66	547.74	62.83
18	28	17	1351.80	562.17	58.41
19	27	17	1542.50	579.88	62.41
20	26	16	1580.91	601.31	61.96
21	25	16	1723.60	623.50	**63.83**
22	24	16	1667.80	675.25	59.51
23	23	15	1717.60	692.69	59.67
24	22	15	1772.17	733.74	58.59
25	21	14	1832.13	780.85	57.38
26	20	14	1863.10	836.20	55.11

The data was collected for discrete points as shown in Table 5.1. However, these values have to be interpolated for intermediary values. The interpolation of the values is shown in Figure 5.1 and Figure 5.2. The interpolated graphs are third degree polynomials with maximum fit. The vales of the coefficient of determination were calculated. A value of 0.96 was determined for 2WS interpolation and a value of 0.99 was obtained for 4WS data interpolation. These values showed the goodness of fit to the values obtained during raw testing.

After interpolation as seen in Figure 5.1 and Figure 5.2, it is possible to compare the data and find out the percentage reduction in TCR by using 4WS over 2WS. The values in the table point towards the reduction obtained by switching the vehicle from 2WS to 4WS. This reduction is a clear indication achieving the aims set at the beginning of this project. A maximum reduction percentage of 63.82 % and a minimum reduction of 49.10 % are observed.

Chapter 6 Conclusion and Future Scope

6.1 Introduction

This prototype and model was developed using SolidWorks 2016 x64 Edition over months of design and subsequent iterations. Following the process and a complete physical prototype was built as per the needs to showcase the working of the proposed steering system.

Having developed the prototype, it is also seen that this can be implemented in other domains, even remotely linked to the automotive industry as well. As depicted in previous chapters, it is showcased how one can implement an electronic system in wheel chairs that can help the disabled with easy manoeuvrability in tight spaces and dead ends. Apart from a wheel chair, this technology can also find its use in the agricultural, construction and heavy industries as well. This system can further be implemented in various ways,

6.2 Total Development Flowchart

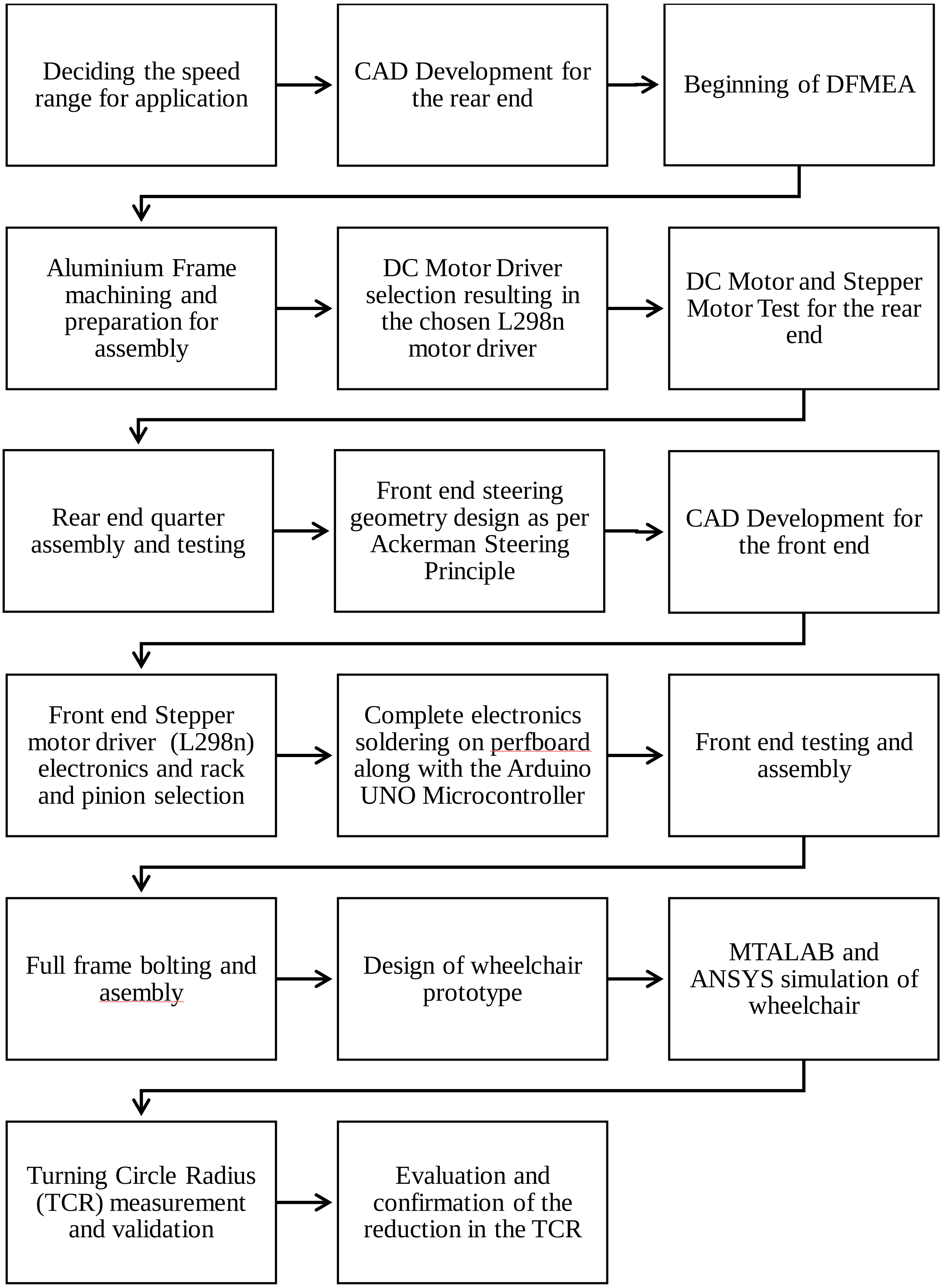


Figure 6.1 Flowchart for Prototype Development

Having conducted tests in various combinations and having recorded all the values, the aim set out to achieve at the beginning of the project has Besides the electro-mechanical layout. The system can be all electrical, which reduces build complexity. Since hydraulics and pneumatics are a huge part of constructional equipments and the heavy Industries, the proposed idea of steering can be implemented with changes to the current system has been sufficiently met. Having aimed at obtaining a TCR s reduction of at least 20%, the prototype built has shown reductions of much larger magnitude. Additionally, it is also noted that the Zero turn steer has played a major role in reducing the TCR to a much smaller amount allowing the vehicle to turn about its own axis. Having received a percentage of TCR reduction from **49.10%** to **63.82%.**

The values obtained were also juxtaposed with the values obtained from the MATLAB code that was used, which can be seen in Appendix 1.

4WS and Zero turn steer as discussed in this report help to significantly reduce the space required by a vehicle to change direction of motion. This will become an important aspect of any vehicle in the years to come with shrinking spaces increased congestion in urban areas. These two features maybe adopted with suitable alterations to the core design for the specific purpose as illustrated in case of a wheelchair. Other areas where this can be extended to include lawn mowers, forklifts or with heavy machinery like agriculture or construction vehicles where swerving around obstacles is important. It is also important to note that 4 wheel steer has been implemented in many production cars to date in various ways [3] while zero turn steer is yet to be implemented in production vehicles. The front steering for the prototype was designed to demonstrate a way in which Zero Turn Steer maybe implemented in vehicles with a conventional Ackermann steering mechanism.

The main challenges expected while implementing this design in a vehicle would be packaging of the components within the limited space available while allowing for the range of motion required by the wheels to execute this manoeuvre as well as ensuring reliability of the entire system over the expected life of the vehicle.

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Appendix 1

This is a MATLAB code developed alongside the project to calculate the turning circle radius given the wheelbase and the wheel track [33]

```
% program to calculate turning circle radius for 2 wheel and 4
wheel steering
% reference: Prof Kanan C, lecture notes, Automotive Chassis,
VIT Vellore, Jan-June 2016

clear all
clc

i=input('Enter (1) for 2 wheel steering, (2) for 4-wheel
steering calculation: ');
if i==1
    clear all
    clc
    disp('        TWO WHEEL STEERING');
    Wb=input('Enter Wheel Base: ');          %Wheel Base
    Wt=input('Enter Wheel Track: ');         %Wheel track
    al=input('Enter front inner wheel turn angle(in degrees,
less than 50°): ');
    if
Wb<=0||Wt<=0||al<=0||al>50||imag(Wb)~=0||imag(Wt)~=0||imag(al)
~=0
        disp('Error, please recheck values');
        return
    end
    al=pi*al/180;                              %front inner turn
angle alpha
    bt=atan(Wb/(Wt+(Wb/tan(al))));            %front outer turn
angle beta
    %calculating all dimensions
    L=Wb/tan(al);
    Tcr=(Wb/sin(bt));                            %Turning circle
radius
    disp(['The turning circle radius is ',num2str(Tcr), '
units']);
    hold on
    grid off
    %plotting the car
    plot([0; Wt], [0; 0], 'LineWidth', 2,'color','b')
    plot([0; 0], [0; Wb], 'LineWidth', 2,'color','b')
    plot([0; Wt], [Wb; Wb], 'LineWidth', 2,'color','b')
    plot([Wt; Wt], [0; Wb], 'LineWidth', 2,'color','b')
    %setting the axises
```

```
    xmin=(0-Wt/3);
    xmax=1.1*(Wt+L);
    ymin=(0-Wb/3);
    ymax=Wb*1.3;
    axis equal
    axis([xmin xmax ymin ymax])
    th=0.25*Wb/2;                              %tyre diameter, as
a fraction of wheel base (aesthetics)
    %plotting rear wheels
    plot([0; 0], [-th; th], 'LineWidth', 5,'color','r')
    plot([Wt; Wt], [-th; th], 'LineWidth', 5,'color','r')
    %plotting dotted lines
    plot([Wt;      Wt+L],      [Wb;      0],      'LineWidth',
1,'color','k','LineStyle','--')
    plot([Wt;      Wt+L],      [0;      0],      'LineWidth',
1,'color','k','LineStyle','--')
    %plotting front wheels
    plot([-th*sin(bt);      th*sin(bt)],      [Wb-th*cos(bt);
Wb+th*cos(bt)], 'LineWidth', 5,'color','r')
    plot([Wt-th*sin(al);    Wt+th*sin(al)],    [Wb-th*cos(al);
Wb+th*cos(al)], 'LineWidth', 5,'color','r')
    %plotting the legend
    plot([0;      Wt+L],      [Wb;      0],      'LineWidth',
1,'color','green','LineStyle','--');
    text((Wt+L)/2,(Wb/2),['\leftarrow Tcr = ',num2str(Tcr), '
units'],'FontWeight','bold');
    hold off

elseif i==2

    % *program to calculate turning circle radius for 4 wheel
drive*
    clear all
    clc
    disp('       FOUR WHEEL STEERING');
    %% taking inputs
    Wb=input('Enter Wheel Base: ');         %Wheel base
    Wt=input('Enter Wheel Track: ');        %Wheel track
    alf=input('Enter front inner wheel turn angle(in degrees,
less than 50°): ');
    if
Wb<=0||Wt<=0||alf<=0||alf>50||imag(Wb)~=0||imag(Wt)~=0||imag(a
lf)~=0
        disp('Error, please recheck values');
        return
    end
    alf=pi*alf/180;                             %front inner turn
angle alpha_front
    %% fitting curve to get rear turn angle vs front
    Fwa=[0, 10, 20, 25, 30, 35, 40, 45];
    Rwa=[0, 4, 0, -9, -19, -27, -36, -45];
```

```
    p=polyfit(Fwa,Rwa,4);
    %Fwa=0:1:45;
    %plot (Fwa,polyval(p,Fwa))
    alr=polyval(p,alf*180/pi);
    alr=alr*pi/180;                                    %rear inner turn
angle alpha_rear
    %% plotting the car
    hold on
    grid off
    th=0.25*Wb/2;
    plot([0; Wt], [0; 0], 'LineWidth', 2,'color','b')
    plot([0; 0], [0; Wb], 'LineWidth', 2,'color','b')
    plot([0; Wt], [Wb; Wb], 'LineWidth', 2,'color','b')
    plot([Wt; Wt], [0; Wb], 'LineWidth', 2,'color','b')
    %% plotting front and rear inner tyres
    plot([Wt-th*sin(alf);   Wt+th*sin(alf)],   [Wb-th*cos(alf);
Wb+th*cos(alf)], 'LineWidth', 5,'color','r')
    plot([Wt+th*sin(alr);   Wt-th*sin(alr)],   [th*cos(alr);   -
th*cos(alr)], 'LineWidth', 5,'color','r')
    %% finding turning radius point
    syms x y
    lri=(tan(-alr)*x)-(tan(-alr)*Wt)-y;                          %line
perpendicular to rear inner wheel
    lfi=-tan(alf)*x+Wb+Wt*tan(alf)-y;                            %line
perpendicular to front inner wheel
    P=solve(lri==0,lfi==0);                                   %Point  of
intersection, turning circle center
    P.x=(double(P.x));
    P.y=(double(P.y));
    %% plotting lines from inner wheels
    plot([Wt;      P.x],      [0;      P.y],      'LineWidth',
1,'color','k','LineStyle','--')
    plot([Wt;      P.x],      [Wb;      P.y],      'LineWidth',
1,'color','k','LineStyle','--')
    %% finding outer wheel angles
    btr=-(atan(P.y/P.x));                              %rear outer turn
angle beta_rear
    btf=atan((Wb-P.y)/P.x);                           %front outer turn
angle beta_front
    %% plotting outer wheels
    plot([th*sin(btr);     -th*sin(btr)],     [th*cos(btr);     -
th*cos(btr)], 'LineWidth', 5,'color','r')
    plot([-th*sin(btf);     th*sin(btf)],      [Wb-th*cos(btf);
Wb+th*cos(btf)], 'LineWidth', 5,'color','r')
    %% plotting turning radius
    if            pdist([0,0;P.x,P.y],'euclidean')              >=
pdist([0,Wb;P.x,P.y],'euclidean')      %checking which tyre is
the farthest
        Tcr=pdist([0,0;P.x,P.y],'euclidean');
        plot([0;      P.x],      [0;      P.y],      'LineWidth',
1,'color','green','LineStyle','--')
```

```
        plot([0;     P.x],     [Wb;     P.y],     'LineWidth',
1,'color','k','LineStyle','--')
    else
        Tcr=pdist([0,Wb;P.x,P.y],'euclidean');
        plot([0;     P.x],     [Wb;     P.y],     'LineWidth',
1,'color','green','LineStyle','--')
        plot([0;     P.x],     [0;     P.y],     'LineWidth',
1,'color','k','LineStyle','--')
    end
    disp(['The  turning  circle  radius  is  ',num2str(Tcr),  '
units']);
    %% Setting the graph
    xmin=(0-Wt/3);
    xmax=2*(Wt);
    ymin=(0-Wb/3);
    ymax=Wb*1.3;
    %axis([xmin xmax ymin ymax])
    axis image
    text(((P.x)/2),P.y+((Wb-P.y)/2),['\leftarrow     Tcr     =
',num2str(Tcr), ' units'],'FontWeight','bold')
    hold off
else
    clear all
    clc
    disp('Error, value incorrect, re-run program');
end
```

Appendix 2

Arduino IDE Programme for Joystick Motion

Steering Code

```
#include <Stepper.h>//importing stepper library
#include <Servo.h>//importing servo library
Servo SR;//declaring the right servo
Servo SL;//declaring the left servo

Stepper myStepper(200, 7,8,9,10); //decaring stepper speed and
pins
const byte LServo =6;  //Right Servo signal pin
const byte RServo =5;  //Left Servo signal pin
const byte stepperEN1=3; //stepper enabler pins 3 and 11
const byte stepperEN2=11;
const int xAxis = A0;   //analogue pin number for joystick
const int steerbuttonpin=A1 ;//steering button pin
const int hydbuttonpin=A2 ;//hydraulic button pin


int steerButtonState; //steering button ON/OFF state
int  hydButtonState;//hydraulic  button  steering  button  ON/OFF
state
int innerangle=0; //variable for the inner angle turned by the
servo
int outerangle=0; //variable for the outer angle turned by the
servo
int x_pos; // corrected X-position of the slider
int x_pos_raw;  //Raw X position

const int servorestL=90; //Left servo rest position (0 angle)
const int servorestR=90; //Right servo rest position (0 angle)
int wantedPos; //Desired position of the joystick
int pos =0;  //actual position of the joystick


int CorVal( int z){
  //  Function  corrects  potentiometer  output  to  make  it  more
linear
      int RET;
      if (z<60){
            RET=z*4.65;
            }
      else if (z<977){
           RET=(0.50708*z)+248.5741;
            }
      else{
            RET=(6.0652*z)-5181.718;
            }
```

```
      return (RET);
  }

void ServoStraightAhead(){
  //function that brings the servo straight ahead to rest
position
  SR.write(servorestR);
  SL.write(servorestL);

}

void StepperTurnSteps( int x){
  //function to turn steps by the desired amount
  digitalWrite(stepperEN1,HIGH);
  digitalWrite(stepperEN2,HIGH);
  //HIGH signal to the stepper enabler pin
  myStepper.step(-x);
  delay(5*abs(x));
  digitalWrite(stepperEN1,LOW);
  digitalWrite(stepperEN2,LOW);
  //LOW signal to the stepper enabler pin
  pos=pos+x;
}

int
InnerAngleArray[]={0,3,6,9,12,15,18,21,24,27,30,33,36,39,42,45
};
//Array of values for inner wheel angles
int
OuterAngleArray[]={0,3,5,7,9,11,13,14,16,17,18,19,20,21,22,23}
;
//Array of values for outer wheel angles

int ChangeAngle(int q){
  //Function to get OuterAngle from InnerAngle
      int res;
      for (int i=0; i<16; i=i+1){
             if (q <= InnerAngleArray[i]){
                   res = OuterAngleArray[i];
                   break;
             }
       }
       return res;
}
void setup() {
  //OUPUT PINS
  pinMode(stepperEN1, OUTPUT);
  pinMode(stepperEN2, OUTPUT);
  //INPUT PINS
  pinMode(xAxis,INPUT);
  pinMode(hydbuttonpin, INPUT);
```

```
  pinMode(steerbuttonpin, INPUT);

  SR.attach(RServo);
  SL.attach(LServo);
  SR.write(servorestR);//brings Rservo to home upon switch on
  SL.write(servorestL);//brings Lservo to home upon switch on
  myStepper.setSpeed(60);
  Serial.begin(9600);
  //to be able to use the serial monitor display for debugging
  analogWrite(stepperEN1,0);
  analogWrite(stepperEN2,0);
  delay(2000);
}
void loop(){
 x_pos_raw =  analogRead(xAxis);
 x_pos=CorVal(x_pos_raw);
 x_pos=(1023-x_pos);
 //Getting the slider valuue, then correcting it
   steerButtonState = digitalRead(steerbuttonpin);
   hydButtonState = digitalRead(hydbuttonpin);
   //taking the current input of the hydraulic & steer button
if (hydButtonState == LOW){
if (steerButtonState==HIGH ) {          //4wheelsteering
      //getting inner angle
    if (x_pos < 512) {
     innerangle = (((512-x_pos)*45)/512);
     outerangle = ChangeAngle(innerangle);
     SL.write(servorestL + outerangle); //Settign left servo
     SR.write(servorestR + innerangle);//Setting right servo
     }
    if (x_pos > 513) {
     innerangle = (((x_pos-513)*45)/512);
     outerangle = ChangeAngle(innerangle);
     SL.write(servorestL - innerangle);
     SR.write(servorestR - outerangle);
      }
}
wantedPos=map(x_pos,0,1023,-90,90);
//mapping the desired position using map function
if (abs(wantedPos-pos)>=10){
  if (pos > wantedPos){
    StepperTurnSteps(-5);}
  if (pos < wantedPos){
  StepperTurnSteps(5);}
  //Turnign stepper based on diff. b/w pos and wantedPos
}
}
if (hydButtonState==HIGH){
  //HydraulicMode,  servos  set  to  fixed  angles,  stepper
centered
  StepperTurnSteps(-pos);
```

```
    delay(1000);
    SL.write(servorestL+30);
    delay(1000);
    SR.write(servorestR-30);
  }
  }
```

DC motor Code

```
const byte LMotorS=10;  //Right wheel motor signal pin
const byte RMotorS=11;  //Left wheel motor signal pin~
const byte LMotorA=7;
const byte LMotorB=2;
const byte RMotorA=3;
const byte RMotorB=4;
const byte HMotorS=5;  //Hydraulic Motor signal pin
const int HMotorA=A4;
const int HMotorB=A5;
const int hydbuttonpin=A3; //hydraulic button pin
int yAxis = A0; //analogue input for joystick
int xAxis = A1; //analogue input for linear potentiometer
int x_pos;
int y_pos;
int hydButtonState; //hydraulic button state
void setup() {
  pinMode(RMotorS, OUTPUT);
  pinMode(RMotorA, OUTPUT);
  pinMode(RMotorB, OUTPUT);
  pinMode(LMotorS, OUTPUT);
  pinMode(LMotorA, OUTPUT);
  pinMode(LMotorB, OUTPUT);
  pinMode(HMotorS, OUTPUT);
  pinMode(HMotorA, OUTPUT);
  pinMode(HMotorB, OUTPUT);
  pinMode(hydbuttonpin, INPUT_PULLUP);
  pinMode(yAxis,INPUT);
  pinMode(xAxis,INPUT);
  Serial.begin(9600);
  //used the serial monitor for code debugging
}
void loop() {
  y_pos = analogRead(yAxis);
  //reading the joystick status
  hydButtonState=digitalRead(hydbuttonpin);
  //reading the hydraulic button state

if (hydButtonState == LOW){
  //Normal steering mode
if (y_pos < 460) {
  //joystick moved backwards, DC motor set reverse
      digitalWrite(RMotorA, HIGH);
      digitalWrite(RMotorB, LOW);
```

```
        digitalWrite(LMotorA, LOW);
        digitalWrite(LMotorB, HIGH);
        analogWrite(RMotorS, 200);
        analogWrite(LMotorS, 200);
        //declaring the speed at 200/255
    }
    else if (y_pos > 562) {
      //joystick moved forward, DC motor set forward
        digitalWrite(RMotorA, LOW);
        digitalWrite(RMotorB, HIGH);
        digitalWrite(LMotorA, HIGH);
        digitalWrite(LMotorB, LOW);
        analogWrite(RMotorS, 200);
        analogWrite(LMotorS, 200);
    }
    else {
      //joystick deadzone, DC motor stopped
        digitalWrite(RMotorA, LOW);
        digitalWrite(RMotorB, LOW);
        digitalWrite(LMotorA, LOW);
        digitalWrite(LMotorB, LOW);
    }
  }
  if (hydButtonState==HIGH){
    //Hyd. mode ON
          analogWrite(RMotorS, 150);
          analogWrite(LMotorS, 150);
          analogWrite(HMotorS, 150);
    while(hydButtonState==HIGH){
      hydButtonState=digitalRead(hydbuttonpin);
      x_pos=analogRead(xAxis);
      y_pos=analogRead(yAxis);
      //Reading joystick, slider and hyd. button
      if (x_pos > 1000 ){

        digitalWrite(HMotorA, HIGH);
        digitalWrite(HMotorB, LOW);
      }
      else if (x_pos < 25){
        //slider is at left end, rack contracting
        digitalWrite(HMotorA, LOW);
        digitalWrite(HMotorB, HIGH);
      }
      else {
        digitalWrite(HMotorA, LOW);
        digitalWrite(HMotorB, LOW);
      }

      if (y_pos > 562){
        //joystick moved forward, CW turn
          digitalWrite(RMotorA, LOW);
```

```
        digitalWrite(RMotorB, HIGH);
        digitalWrite(LMotorA, LOW);
        digitalWrite(LMotorB, HIGH);
    }
    else if (y_pos < 460){
      //joystick moved backwards, ACW turn
        digitalWrite(RMotorA, HIGH);
        digitalWrite(RMotorB, LOW);
        digitalWrite(LMotorA, HIGH);
        digitalWrite(LMotorB, LOW);
    }
  else {
        digitalWrite(RMotorA, LOW);
        digitalWrite(RMotorB, LOW);
        digitalWrite(LMotorA, LOW);
        digitalWrite(LMotorB, LOW);

   }
   }

}
}
```

Arduino IDE Programme to make the prototype move along a prescribed path .

```
#include <Stepper.h>
#include <Servo.h>
Servo SR;
Servo SL;
Stepper myStepper(200, 7,8,9,10);
const byte RServo =2;  //Right Servo signal pin
const byte LServo =3;  //Left Servo signal pin   ~
const byte LMotorS=5;  //Rigth wheel motor signal pin
const byte RMotorS=6;  //Left wheel motor signal pin~
const byte LMotorA=45;  //Right motor inA
const byte RMotorA=47;  //Left motor inA
const byte LMotorB=49;  //Right motor inB
const byte RMotorB=51;  //Left motor inB
const byte stepperEN1=3;
const byte stepperEN2=11;
//Hydraulic DC motor
const int servorestR=88;    //Servo resting angle,  when
upside down, to turn the LEFT WHEEL Clockwise, we need to ADD
angles
const int servorestL=95;    //Servo resting angle. when upside
down, to turn the RIGHT WHEEL Clockwise, we need to SUBSTRACT
angles
int pos =0;
void DCmove(int k){
      digitalWrite(RMotorA, HIGH);
```

```
      digitalWrite(RMotorB, LOW);
      digitalWrite(LMotorA, LOW);
      digitalWrite(LMotorB, HIGH);
      analogWrite(RMotorS, 200);
      analogWrite(LMotorS, 200);
      delay(1000*k);
      digitalWrite(RMotorA, LOW);
      digitalWrite(RMotorB, LOW);
      digitalWrite(LMotorA, LOW);
      digitalWrite(LMotorB, LOW);
}
void ServoStraightAhead(){
  SR.write(servorestR);
  SL.write(servorestL);
}
 void StepperTurnSteps( int x){
  digitalWrite(stepperEN1,HIGH);
  digitalWrite(stepperEN2,HIGH);
  myStepper.step(x);
  delay(200/abs(x));
  digitalWrite(stepperEN1,LOW);
  digitalWrite(stepperEN2,LOW);
  pos=pos+x;
}
void setup() {
  // put your setup code here, to run once:
    // set the speed at 60 rpm:
  pinMode(RServo, OUTPUT);
  pinMode(LServo, OUTPUT);
  pinMode(RMotorS, OUTPUT);
  pinMode(RMotorA, OUTPUT);
  pinMode(RMotorB, OUTPUT);
  pinMode(LMotorS, OUTPUT);
  pinMode(LMotorA, OUTPUT);
  pinMode(LMotorB, OUTPUT);
  pinMode(stepperEN1, OUTPUT);
  pinMode(stepperEN2, OUTPUT);
  SR.attach(RServo);
  SL.attach(LServo);
  SR.write(servorestR);
  SL.write(servorestL);
  myStepper.setSpeed(60);
  // initialize the serial port:
  Serial.begin(9600);
  delay(3000);
}
void loop() {
      DCmove(3);//making the rear DC motors move forward for 3 
seconds
      //FOUR WHEEL STEER CODE
      SL.write(servorestL-23);//turning the rear servos
```

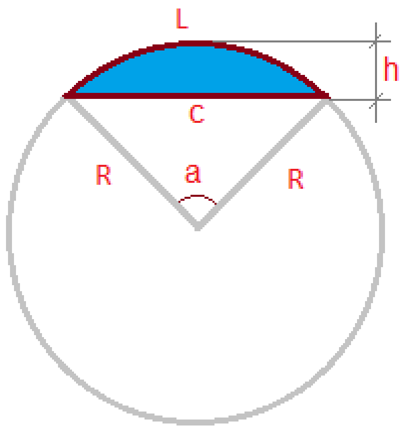
```
        SR.write(servorestR-45);
        StepperTurnSteps(64);
        delay (1000);
        DCmove(3);
        ServoStraightAhead();//resting the servos
        StepperTurnSteps(-64);
        delay (1000);
        //CRAB STEER MODE
        SL.write(servorestL-23);//turning the rear servos
        SR.write(servorestR-45);
        StepperTurnSteps(-64);//again -64 for the wheel to turn
to LEFT turn direction
        DCmove(3);
        ServoStraightAhead();//resting the servo motor
        StepperTurnSteps(64);//resting the stepper motor
        delay(2000);
        //ZERO STEER CODE
        SR.write(servorestR+45);
        SL.write(servorestL-45);//turning the rear servos
        delay(1000);
        digitalWrite(RMotorA, HIGH);
        digitalWrite(RMotorB, HIGH);
        digitalWrite(LMotorA, LOW);
        digitalWrite(LMotorB, LOW);
        analogWrite(RMotorS, 200);
        analogWrite(LMotorS, 200);
        delay(4000);
        digitalWrite(RMotorA, LOW);
        digitalWrite(RMotorB, LOW);
        digitalWrite(LMotorA, LOW);
        digitalWrite(LMotorB, LOW);
        ServoStraightAhead();
        delay(100000);
}
```

Appendix 3

Calculation of TCR using chord and arc length

Suppose a circle with radius R units, Chord length of c, Arc length of L units and an angle traversed of a degree. The said circle is depicted in the image 47.

The calculation that is used also follows the figure.



Circle for Calculation Reference

$$L = a.R$$

$$C = 2.R.sin\left(\frac{a}{2}\right)$$

Appendix 4

Table A-1 DFMEA Detection Table [34]

Detection	Criteria: Likelihood of Detection by Design Control	Ranking
Almost Uncertainty	Design Control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no Design Control	10
Very Remote	Very remote chance the Design control will detect a potential cause/mechanism and subsequent failure mode	9
Remote	Remote chance the Design control will detect a potential cause/mechanism and subsequent failure mode	8
Very Low	Very low chance the Design control will detect a potential cause/mechanism and subsequent failure mode	7
Low	Low chance the Design control will detect a potential cause/mechanism and subsequent failure mode	6
Moderate	Moderate chance the Design control will detect a potential cause/mechanism and subsequent failure mode	5
Moderately High	Moderately high chance the Design control will detect a potential cause/mechanism and subsequent failure mode	4
High	High chance the Design control will detect a potential cause/mechanism and subsequent failure mode	3
Very High	Very high chance the Design control will detect a potential cause/mechanism and subsequent failure mode	2
Almost Certain	Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode	1

Table A-2 Severity Rating Table [34]

Effect	Criteria: Severity of Effect	Ranking
Hazardous - Without warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning	10
Hazardous - With warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning	9
Very High	Vehicle/item inoperable, with a loss of primary function	8
High	Vehicle/item operable, but at reduced level of performance. Customer dissatisfied	7
Moderate	Vehicle/item operable, but Comfort/Convenience item(s) inoperable. Customer experiences discomfort	6
Low	Vehicle/item operable, but comfort/Convenience item(s) operable at reduced level of performance. Customer experiences some dissatisfaction	5
Very Low	Fit & Finish/Squeak & Rattle item does not conform. Detect noticed by most customers	4
Minor	Fit & Finish/Squeak & Rattle item does not conform. Detect noticed by average customer	3
Very Minor	Fit & Finish/Squeak & Rattle item does not conform. Detect noticed by discriminating customer	2
None	No effect.	1

Table A-3 Occurrence Rating Table [34]

Probability of Failure	Possible failure rates	Ranking
Very High: Failure almost inevitable	1 in 2	10
	1 in 3	9
High: Repeated failures	1 in 8	8
	1 in 20	7
Moderate: Occasional failures	1 in 80	6
	1 in 400	5
	1 in 2,000	4
Low: Relatively few failures	1 in 15,000	3
	1 in 150,000	2
Remote: Failure is unlikely.	1 in 1,500,000	1

Appendix 5

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ADVANCED ALL-WHEEL STEERING FOR ALL TERRAIN VEHICLES

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Abstract: The vehicle steering system is an integral part of the vehicle dynamics of the automobile. While conventional steering system can perfectly perform the work of guiding the vehicle along straight line or curved paths, it is ridden with inherent drawbacks. These drawbacks include increased turning circle radius, reduction in high speed turning stability and the inability to perform a zero turn steer. Under steer and over steer characteristics have also not helped advocate conventional steering systems. The work proposed in this paper, deals with the inculcation of Crab Steer, Four-Wheel Steer and Zero turn steer into one comprehensive steering system package using electric motors. Crab steer helps with high speed turning ability. Four wheel steer turns the wheels in the opposite direction and aids with reduced low speed turning circles. Zero steer enables the vehicle to turn about its vertical axis so that, the vehicle can be maneuvered at dead-ends and tight spaces without much effort upon request. The proposed system is seen to greatly reduce the values of Turning Circle Radius. A reduction of 30 percent was observed during the simulation. The application of this work is endless. It can be of help to the agriculture and the commercial industry. Tractors, All terrain vehicles and off-roaders can now have a wider range of steering ability. Passenger cars can benefit with high stability lane change and easier navigation around parking lots.

I. INTRODUCTION

A. History of Four Wheel Steer

The steering system of a vehicle is an essential component to impart stability to the vehicle while travelling in a straight line and around corners, both during low speed and high speed
maneuvers. While conventional steering system (2WS) can prove to be the most optimal solution, both from a complexity and an economical front, it puts forth a huge room for improvement in various other real world situations. These include:

- High Speed Turns and Lane Changing
- Low speed tight corners
- Navigating at dead end

These challenges have driven research to new directions and have given a plethora of innovative solutions, including the concept of Four Wheel steering (4WS). The first car to deploy this technology was the Nissan Skyline GT-R. The system was called the High Capacity Actively Controlled Steering (HICAS), was back in 1986. [1] In this steering system the variation in turning direction of the rear wheels with respect to the front wheels will determine the change in vehicle dynamics. Two separate concepts of in-phase steering and counter-phase steering will are employed which are explained in detail in the subsequent chapters.
The 4WS upon varying the turning angles of the individual wheels effectively reduces the wheelbase of the vehicle. Hence, the driver will feel like he is driving a vehicle shorter in length than it actually is, which can enable him to drive out of parking spaces with minimal effort and relative ease.
All terrain vehicles such as tractors, dune buggies and other off road vehicles find themselves negotiating tight corners and high speed maneuvers all the time. This project aims to develop a steering system for just that, while inculcating an added mode of Zero Turn Steer.

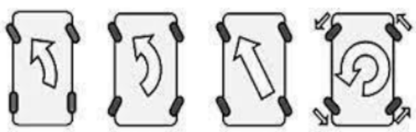


Fig 1.1 Example of Various Steering Mechanism [2]

B. Various Steering Wheel configurations

- Two Wheel Steer: In this mode only one axle is driven.
- Four wheel steer: In this case, both axle are driven but in direction opposite to each other.
- Crab steer: When all the wheels turn in same direction it is known as crab steer.
- Zero turn steer: In this mode vehicle follows the circular path.

C. ***Modern Steering Mechanism***

Most modern vehicles are steered based on the Ackermann steering mechanism. A pinion is attached to the end of the steering wheel shaft, which meshes with a linear gear or rack. The rotational input of the driver is then fed to the wheels by converting it to translation motion by the rack and is fed to the wheels.

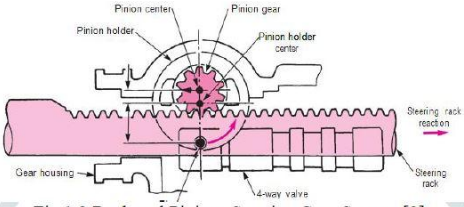


Fig 1.2 Rack and Pinions Steering Gear System [3]

The mechanism that actuates each wheel for the appropriate amount of toe in/out is known as the Ackermann mechanism.

D. Zero Turn Steer

Zero turn steering involves changing the wheel angles of the front and rear wheels such that the vehicle can turn about its geometric centre, making the theoretical turning radius zero. The immense number of advantages this system would potentially provide to the driver are only overshadowed by the impracticalities in its application in a real vehicle, ranging from the opposite-turning wheels on the same axle to changing the direction of rotation of half of the driven wheels [2], [4]. Still, some vehicles have demonstrated this concept like the Jeep Hurricane [5].

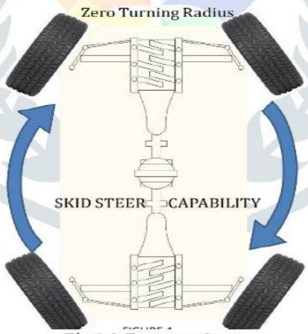


Fig 1.3 Zero-turn Steer

Advantages [6] [7]

- Superior cornering

The vehicle can take turns around smaller corners, in roads with lesser width. Or, it is better equipped to take turns of more than 90 degrees over a conventional vehicle.

- Improved steering response

Since the rear assist is electronically controlled, the overall steering response would be smoother at any vehicle speed.

- High speed stability and lane changing

As the crab steer kicks in at high speeds, the vehicle will feel more stable and in-control while changing lanes, can perform this maneuver faster.

- Smaller turning radius

The point about which the vehicle turns is closer to the geometric centre of the vehicle as the rear wheel toe increases out-of-phase, giving a smaller turning circle radius which is helpful in situations like turning, parking, and backing out of tight corners, maneuvering in tight spaces and taking U-turns.

Disadvantages

- Chance of electrical failure

This system depends so much on sensors, controllers ECU's and other electrical components, so the chance of any electrical component failing increases. This failure may lead to catastrophic accidents due to the steering system going haywire, and safety protocols in the case of electronic failures need to be set up before this system is implemented. [7]

- Space and complexity

Additional components require space, which need to be fitted near the wheel hub and suspension systems, an area which is already crowded. Apart from packaging problems, these components increase overall complexity of the system, potentially creating additional failure modes which need to be addressed.

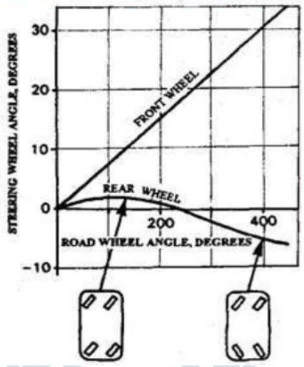


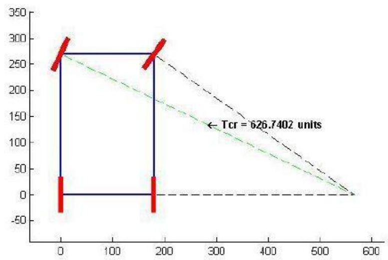
Fig 1.4 Relation between Steering Wheel angle and Road wheel turning angles (Front and Back) [8]

II. MATLAB MODEL SIMULATION

For simulating two wheel steering, standard Ackermann criteria is followed to calculate the outer wheel angle. This is done by assuming the vehicle to be turning about a point lying on a line passing through the rear axle, and both the wheels should be perpendicular to the line joining this point and the pivot point at the axle, to draw geometrical constraints which were converted to equations. This allows us to calculate and plot the outer wheel angle, as well as the turning circle radius which can be taken as the distance between the outer front wheel and the point on the rear axle extension about which the vehicle is turning.
At low speeds, the 4-wheel turning allows for sharper turns, and at higher speed the crab steer makes the vehicle more stable while changing lanes. To decide if the turning should be in-phase steer or out-of-phase steer, we calculate the angle turned by the rear wheels as a function of vehicle speed and a function of front wheel turning angle. At low speeds, a typical driver requires minimum turning circle radius. Conversely, at high speeds the vehicle is steered subtly to shift lanes or follow the road bends. So it becomes convenient to use the front steering angle as a parameter in the function that controls the rear wheel toe angle.
To generate that function, we have the following constraints:

a) The rear wheels should turn with the front wheels to certain angle, then turn in the opposite side when the angle is increased above a certain value
b) The change in turn direction should not be too sudden
c) The rear wheels should never turn more than the front wheels in the same direction, as that would cause the car to turn in the opposite direction as intended.

Consulting existing literature, and using a curve-fitting tool in MATLAB, we generated a 4th degree polynomial from a set of points which the rear wheel angle should suffice when the front wheel angle is at a particular value. After getting the rear inner wheel angle for any value using this polynomial, we can apply a modified Ackermann criterion to calculate the outer wheel toe. To calculate them we assume the instantaneous point around which the vehicle is turning is a point formed by the intersection of perpendiculars drawn from the inner wheels, whose angles have already been decided. Then the outer wheels should turn such that they are perpendicular to the same point. Using this modified Ackermann criteria, we can calculate the outer wheel angles and plot them for a visualization of 4 wheel steering and obtain the turning radius, which is simplified as the distance between the outer front wheel centre and the instantaneous turning point.
The concept prototype can be understood by looking at the front and rear halves separately. The front is constructed based on traditional Ackermann geometry and the wheels are steered using a movable rack that is attached to the wheels using a tie rod. The geometry is designed so that at exactly 45 degrees of toe out for the inner wheel, the instantaneous centre of the mechanism occurs equidistant from the front and rear pivot points. This is done to enable 4WS about the centre line of the car which greatly reduces turning circle radius.



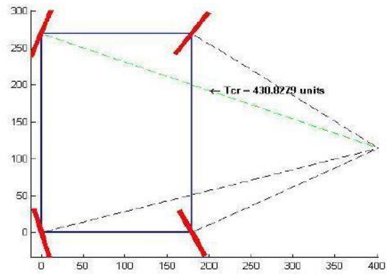


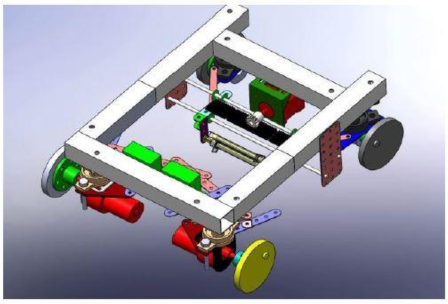
Fig 2.1 Simulation results for (a) 2WS and (b) 4WS
MATLAB Simulation

III. PHYSICAL MODEL

The rack length is also governed by a hydraulic system attached to a DC motor. Under zero steer condition, the hydraulic system enables the rack to be extended so that perpendiculars drawn from the centre of each wheel intersects at the geometric centre of the prototype to enable it to turn about its vertical axis.

The rear wheels are coupled with one DC motor each that powers the forward and reverse motion of the prototype. They are steered by a servomotor connected via a double crank mechanism. The toe of each of the rear wheels are thus governed by servomotors.

The stepper motor (employed to actuate the rack), DC motors and the servo motors are controlled by an Arduino MEGA controller board coupled with DC motor and stepper motor drivers. The code stored on the Arduino gives the instructions for each motor on the prototype regarding speed, angle and position of each motor allowing us to accurately control the vehicle. A 6V battery on board supplies the power for the motors, motor drivers and the Arduino. The prototype has three modes of operation: 4WS, Crab steer, and Zero turn steer.



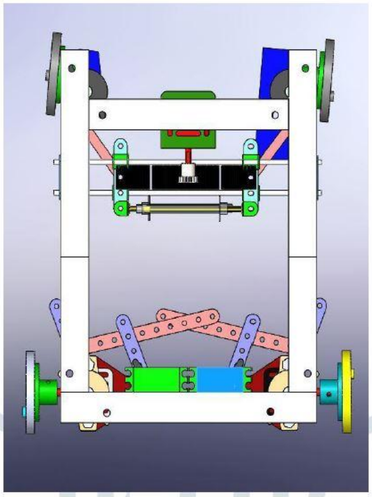


Fig 3.1(a) Top view of the CAD Model (b) Front three quarter view of the CAD Model

At low speeds, it employs counter phase steering i.e. the rear wheels are steered in a direction opposite to that of the front wheels. This greatly reduces the turning circle radius.
At high speeds, it employs in-phase steering enabling lane change with minimal load transfer and ensuring stability of the car. When the prototype is stationary, the hydraulics allows the rack length to be modified so that the car may turn about its vertical axis and achieve a zero turning circle radius.

IV. RESULTS

Turning Circle Radius of the vehicle was measured before and after implementing 4 wheel steering using IS12222 standard, and the data was correlated with theoretical values obtained via simulations.
As the data shows, experimental values correlate with theoretical values of Turning Circle Radius, and a marked decrease in Turning Radius is shown at high steering angles.

Table 4.1 Simulation results for (a) 2WS and (b) 4WS
MATLAB Simulation

Front inner wheel turning angle (degrees)	Two wheel steering		Four wheel steering	
	Front outer wheel angle (degrees)	Turning Circle Radius (m)	Front outer wheel angle (degrees)	Turning Circle Radius (m)
0	0	infinity	0	infinity
5	4.73	3277.26	4.9	11002.35
10	8.97	1732.42	9.4	3082.02
15	12.81	1217.96	13.16	1465.81
20	16.33	960.55	16.08	904.29
25	19.58	805.61	18.26	649.56
30	22.63	701.68	19.88	512.98
35	25.52	626.74	21.12	430.82
40	28.28	569.80	22.16	377.85
45	30.96	524.79	23.26	343.92

V. FUTURE SCOPE

This technology can find its application in Forklifts, agriculture, construction as well as off-road vehicles. It may also be employed for domestic applications like wheelchairs in hospitals where they may have to navigate through narrow corridors. The purpose of building the front end hydraulic was to make sure it can be used in tandem with other systems who has hydraulics employed in their functioning. The front end was designed based on traditional steering systems used in vehicles that are mass manufactured to show compliance with current industry steering systems

VI. CONCLUSION

Using Four Wheel Turning mechanism, the vehicle is more maneuverable around turns and the Zero Turn allows it to turn on the spot making it ideal for parking and reversing. Four Wheel Steering at high angles reduce the turning radius by over 30%, making it an ideal system to implement in any vehicle for stability, convenience and flexibility if practical problems of packaging and suspension integration could be overcome.

Using Four Wheel Turning mechanism, the vehicle is more maneuverable around turns and the Zero Turn allows it to turn on the spot making it ideal for parking and reversing. Four wheel steering at high angles reduce the turning radius by over 30%, making it an ideal system to implement in any vehicle for stability, convenience and flexibility if practical problems of packaging and suspension integration could be overcome.

VII. ACKNOWLEDGEMENT

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Appendix 6

Measurement of Turning Circle Diameter of Vehicles as per IS-12222

Aim: To measure the & Turning Circle Clearance diameter (TCD) & Turning Circle Clearance diameter (TCCD) of Automotive Vehicles

Standard: IS-12222

Measurement Equipment:

- Tyre pressure gauge
- Tyre tread depth gauge
- Weighing system
- Dry bulb & Wet bulb temperature measuring system
- Wind meter
- Atmospheric pressure measuring system
- Measuring tape
- Line Marker
- Water jet

Definitions:

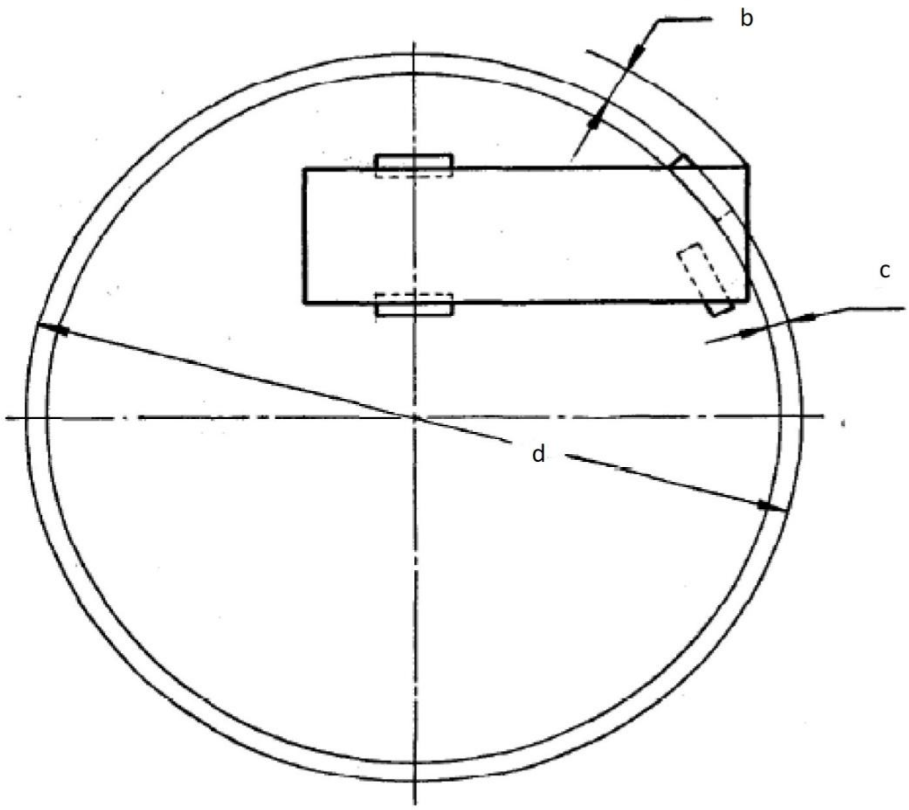
- Turning circle diameter -The diameters of the circle circumscribing the extensions on the supporting plane of mid planes of the steered wheels (the steering wheel being turned to full lock)
- Turning Clearance Circles- The diameter of the largest circle beyond which are located the projections onto the supporting planes of all the points of the vehicle.

Preparation of the Vehicle

- The vehicle shall be fitted with tyres which shall have a tread depth of not less than 90% of the tread depth on new tyre and shall be inflated to the pressure recommended by the manufacturer.
- The measurement may be carried out in laden or unladen condition of the vehicle,
- Check and adjust the steering geometry in accordance with IS: 12159-1987
- The wheel lock angles shall be adjusted to the manufacturer's specification

Measurements

- With the wheels turned to the right/left extreme, transcribe the locus of the front outer wheel by driving the vehicle at a speed not exceeding 5km/h.
- For getting the path of the wheel clearly, suitable method such as wetting the tyre with water or the use of dust may be resorted to.
- Stop the vehicle with steering wheel held rigidly so that the steered wheel continues to be stationary on its transcribed path. By use of a plumb line, make a marking on the ground, of the point projecting the maximum from the transcribed circle.
- This point shall be selected by visual judgement and where it is doubtful, various such points may be projected and the extreme point taken into account.



Turning Circle Measurement **[6]**

- Measure the outer diameter of the circle transcribed by the front outer wheel shown above and subtracts one width of the contact path (as shown c).

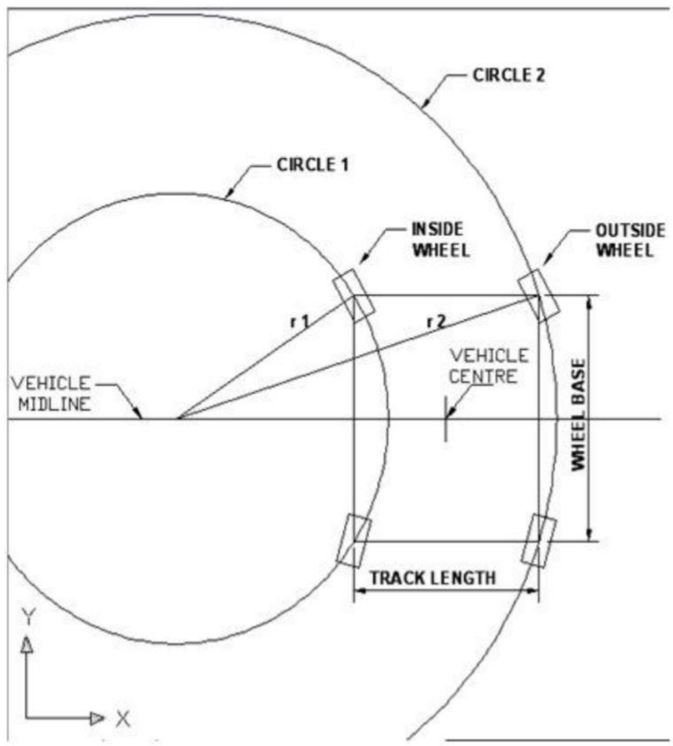
Hence the turning circle diameter (outer) is calculated as:

TCD (outer) = d-c

- Measuring the radial distance (a) in the image below, between the circles and the point marked. Twice this distance shall be added to the measured value of outer circle diameter.
- This shall be TCCD (outer) for left turn.

TCCD (outer) = d+2

- These measurements shall be repeated for the left/right lock.



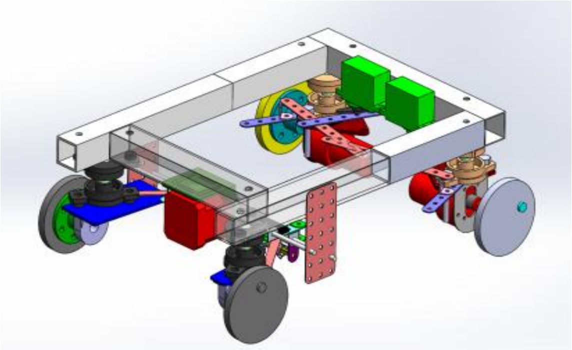
Turning circle radius measurement for inner and outer wheels **[7]**

Appendix 7

Vehicle Prototype Bill of Materials

4WS Prototype with zero turn steer

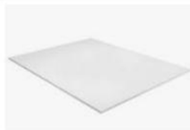
Assembly Name :	Model for 4WS + ZeroTurn
Assembly Number :	1
Assembly Revision :	1
Approval Date :	04-May-19
Part Count :	189
Total Cost :	INR 9,913.00



Part #	Part Name	Description	Qty	Picture	Unit Cost	Total Cost
1	DC Motor	12V 60rpm Brushed DC Motor	2		429	858
2	Flange Bearing	10mm Flange Bearing with 6mm bore	8		190	1520
3	DC Motor Bracket	Anodised bracket for DC hub motor	2		155	310
4	Wheel Hub	High carbon steel wheel hub (6mm center bore, 4mm X 6 peripheral bores)	4		350	1400
5	Wheels	10mm width plastic wheels with 6 slots	4		20	80
6	4mm Rod	High surface finish 4mm dia steel rod (220 mm length)	2		25	50

7	Dowel Pin (10 mm)	Chamfered, precision manufactured Dowel pin	4		12	48
8	Dowel Pin (6 mm)	Chamfered, precision manufactured Dowel pin	2		10	20
9	Frame section	Aluminum 25mm X 25mm hollow frame section (non-uniform thickness)	1		50	50
10	Mechanix 7X1	Slainless steel sheet cut and drilled to size	2		8	16
11	Mechanix 5X1	Slainless steel sheet cut and drilled to size	6		6	36
12	Mechanix 7X3	Slainless steel sheet cut and drilled to size	2		16	32
13	Mechanix 3X2	Slainless steel sheet cut and drilled to size	2		7	14
14	Mechanix 3X1	Slainless steel sheet cut and drilled to size	6		4	24
15	Mechanix L-type	Slainless steel sheet cut, bent and drilled to size	2		4	8
16	Mechanix C-type	Slainless steel sheet cut, bent and drilled to size	12		5	60
17	Plastic Spacer (big)	20mm plastic spacer	4		2	8
18	Plastic Spacer (small)	10mm plastic spacer	6		1	6

19	Servo Motor	MG995 1.2Nm 180 degree motion servo (rated at 6V)	2		380	760
20	Stepper Motor	1.8 Nm two-phase 200 steps/revolution stepper motor	1		733	733
21	Stepper Motor bracket	Anodised bracket for stepper motor	1		165	165
22	Zip Ties	Plastic zip ties	10		0.5	5
23	Gear rack	Nylon 42-teeth 1-module 120mm rack	1		149	149
24	Gear Pinion	15mm pitch dia 1-module plastic pinion gear	1		45	45
25	Syringe (big)	Medical syringe 9 ml	2		18	36
26	Syringe (small)	Medical syringe 4 ml	2		16	32
27	Hydraulic pipe	Rigid polymer pipe resistant to expansion, rated for 10 bar	1		40	40
28	BO motor	DC Motor rated at 5V with coupled plastic gearbox (1:15)	1		90	90
29	Screw-Nut coupling	Plastic high-pitch screw with coupled nut	1		32	32
30	Wooden board	Ply wood board 100mm X 170mm	2		20	40

31	5mm-5mm Coupler	Shaft coupler with grub screws for 5mm - 5mm shaft connection	1		150	150
32	Arduino UNO	Arduino UNO 5V microcontroller	2		450	900
33	L298N motor driver	H-bridge DC motor / stepper motor driver with heat sink	3		280	840
34	Jumper wires set	Multi-core jumper cables	2		30	60
35	Plastic electronics base	0.5mm plastic sheet	1		10	10
36	DC Adaptor	AC 220V to DC 13.6V adaptor convertor	1		150	150
37	Electrical Headers set	Perfboard headers for jumper connectiions	2		20	40
38	Electrical Wires	Multi-core 5A electrical wires	8m		15/m	120
39	10 Ohm resistance	10 watt 10 Ohm wirebound resistor	2		20	40
40	10k ohm resistance	10 ohm film-type low wattage resistor	2		10	20
41	Sliding Potentiometer	10k Ohm resistance sliding potentiometer	1		349	349
42	Joystick	X-pos and Y-pos joystick with button output (10k Ohm pot. for each axis)	1		140	140

43	Switch	On-off switch (small)	2		60	120
44	4mm small length bolts	Bolts with very small nominal length (5mm)	1		75	75
45	6mm Bolts	Standard M6 bolts	12		6	72
46	4mm bolts	Standard M4 bolts	8		5	40
47	4mm Allen bolts	Standard M4 bolts with allen hex head	4		12	48
48	4mm Nuts	Standard nuts for 4mm bolts	12		2	24
49	6mm nuts	Standard nuts for 6mm bolts	12		2	24
50	4mm washers	Standard washers for 4mm nuts	12		1	12
51	6mm washers	Standard washers for 6mm nuts	12		1	12
	Total		**189**			**9913**

Wheelchair prototype Bill of Materials

Assembly Name :	Electric Wheelchair
Assembly Number :	1
Assembly Revision :	1
Approval Date :	04-May-19
Part Count :	107
Total Cost :	INR 88,451.00

Part #	Part Name	Description	Qty	Picture	Unit Cost	Total Cost
1	DC Wheel motors	500W 24V DC 2750 RPM	2		7689	15378
2	Steel frame	Mild steel 25mm section bar	35 Kg (10 m)		38 /Kg	1330
3	Wheel	Rubber wheel 160 mm, 140 Kg load bearing capacity	4		500	2000
4	Stepper motor	87 kg-cm Hybrid Stepper Motor	2		7348	14696
5	Arm rest	25 x 25 x 40 inches foam Armrest	2		1125	2250
6	Battery	24V Li-ion battery pack 11000mAh, 30X Li-ion 3.7V 2200mAh cells	1		7995	7995
7	Controller	Arduino MEGA	1		750	750
8	Stepper Driver	MA860H Digital Stepper Micro-Step CNC Motor Driver 50-110 VDC with 1.8-7.5A	4		6667	26668
9	Coupler	12mm Flexible Clamp Jaw Shaft Coupling	8		350	2800
10	M12 rod	Motor-wheel shaft	4		160	640

11	Bottom cushion	Chair base solid cushion	1		500	500
12	Back cushion	Grey back cushion	1		990	990
13	Footrest	Vissco Wheel Chair Foot Rest	2		813	1626
14	Bearing	12mm Deep Groove Ball Bearing 28mm	4		350	1400
15	U clamp	L2701 25 mm Saddle Pipe U-Clamp	12		509	6108
16	Hose clamp	Width(mm): 9 Diameter(mm): 12-20	4		70	280
17	M12 Bolt	M12 Bolt	18		20	360
18	M12 Nut	M12 Nut	18		8	144
19	M12 washer	M12 washer	18		2	36
20	User joystick	Joystick and button module for wheelchairs	1		2500	2500
			107			**88451**

The Team

This project was carried out by three Bachelor of Technology students pursing Mechanical Engineering (specialized in Automotive Engineering) at the Vellore Institute of Technology, Vellore. The final year was carried out at the Automotive Research Association of India – Forging Industry Division (ARAI - FID).

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