# Steer-By-Wire

# Graduation Project

Ain Shams University

Faculty of Engineering

Mechatronics Department

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# Steer-By-Wire

# Project

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# Abstract:

The 20th century was full of innovations in the field of automation in various industries. X-by-wire systems replace more and more traditional mechanical and hydraulic control systems.

"By-wire" systems refer to the physical connection between operator command devices and the controlled sub-system, such as the connection between the steering wheel and the steering mechanism in a steer by wire system.

In these handouts, through eight chapters, we have covered searches, designs and way of implementation of our steer-by-wire system, as follows:

## Chapter 1:
*An introduction to steer-by wire technology, Description of the system, Motivations and Challenges that face this new technology.*

## Chapter 2:
*This chapter argues the steering system design according to VDI 2206 guidelines.*

## Chapter 3:
*Throughout this chapter we are focusing on different steering system mechanisms like Pitman arm plus many others.*

## Chapter 4:
*Mechanical Test Bed Design and some photos for the real system plus the working drawing for the system parts.*

## Chapter 5:
*This chapter can be considered as control PART ONE as it deals with the motor selection and testing the motor through an experiment in the college workshop to measure its stall torque and stall current. Furthermore, it explains the H-Bridge concept and design circuit.*

## Chapter 6:
*Control PART TWO, as in this chapter we shows the electrical circuits designs for the control circuit using a PIC microcontroller.*

## Chapter 7:
*TESTING, VERFICATION AND VALIDATION.*

## Chapter 8:
*Future Recommendations for steer by wire system.*

# *Chapter 1*

## *Introduction to Steer – By – Wire Technology*

# *CHAPTER 1*

## *1.1.Short Summary:*

The 20th century was full of innovations in the field of automation in various industries. X-by wire systems replace more and more traditional mechanical and hydraulic control systems. It is a generic term for various applications, where electronic control systems are in use. [1]

In automotive environment the ”X” stands for the commanded action such as accelerating, braking and steering. [1] This idea is certainly not new to airplane pilots; many modern aircraft, both commercial and military, rely completely on fly-by-wire flight control systems. [11]

AUTOMOBILE steer-by-wire (SBW) technology refers to next-generation steering systems where mechanical complexity in conventional steering systems is replaced by intelligent mechatronic solutions. Steer-by-wire technology is characterized by the absence of mechanical linkages between the road wheels and the operator interface -usually a hand wheel.[12]

Steer by wire is future automotive technology where **No** mechanincal connection between hand wheel and road wheel.[13]

Unlike the conventional steering system where a hand-operated steering wheel is used to turn the front wheels through the steering column, steer-by-wire technology removes the mechanical and physical links between the driver (steering wheel) and the front wheels, and replace them with electronic actuators and other components.[2]

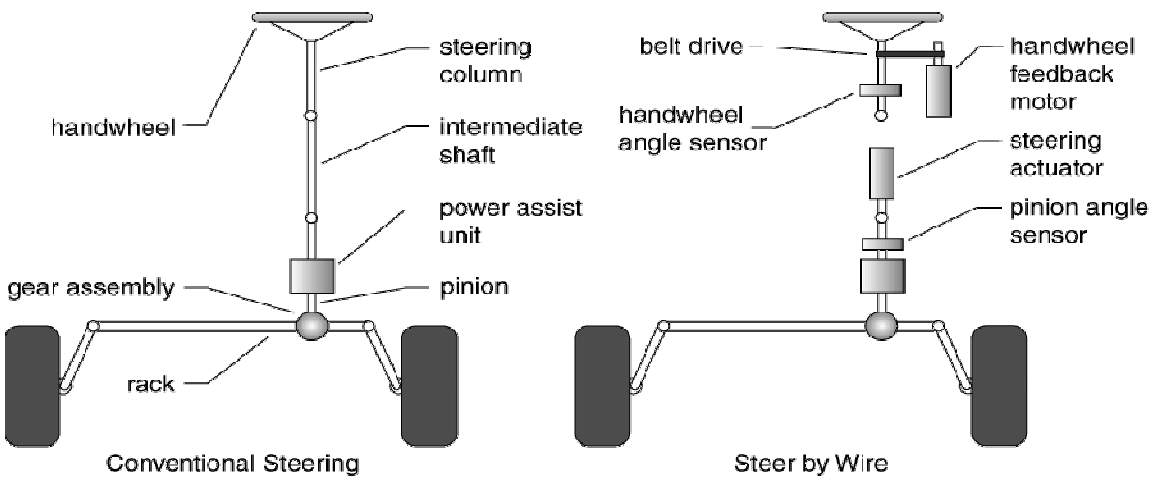



*Fig1.1. Conventional Steering versus Steer by wire*

A steer- by- wire car still has the same old steering wheel and pedals, but they are connected to nothing but a computer chip, which makes driving a bit like playing a video game. The chip monitors what the driver is doing with the steering wheel and pedals, and signals small electric motors to turn the front wheels.[5]

The steer by wire system has the benefit to combine the advantages of old steering systems like the active front steering system and the electrically assisted steering. [14]
Real steer-by-wire systems consist of several sensors, electro motors and controllers. Sensors, connected with the steering wheel, capture the input of the driver. Because there is no mechanical connection to the steering wheel, new innovative input forms, such as sticks, are possible to implement. [1]

Different Steer-by-Wire strategies have been reported in the literature. Some of these approaches only use local feedback (i.e. the steering wheel angle) to produce a reaction torque, computed so as to give a comfortable driving feel. However, real road information is not transmitted to the driver. As this way to compute the reaction torque does not reflect measured road forces, the driver is not aware of the hazards of the road, such as variations of the road surface conditions, curbs or also ruts. [6]

### *1.2.Components of Steer by Wire System: [8]*

Steer-by-wire is based on mechanics, microcontrollers, real-time software, electro motors, power electronics and digital sensors as follows:

- Sensors for rotation angle and torque of steering wheel and front tires. Sensors must be miniaturized to minimize moving masses and to save energy and space under the motor hood. Sensors Also must have a built-in standardized digital interface for computer read-out.
- Actuators (Electro motors) for steering-wheel force feed-back and active tire movement.
- Power electronics required to drive the electro motors: Power electronics must be transistor-based since no AC current is available on board.
- Feed-back controllers to ensure correct steering angle and force feed-back controllers are microprocessor-based and contain real-time software and operating system.
- Mechanical components such as gear, overriding gear, steering wheel, torsion bar, pinion, gear rod and tyres.

*All components have to be merged to a mechatronic system.*

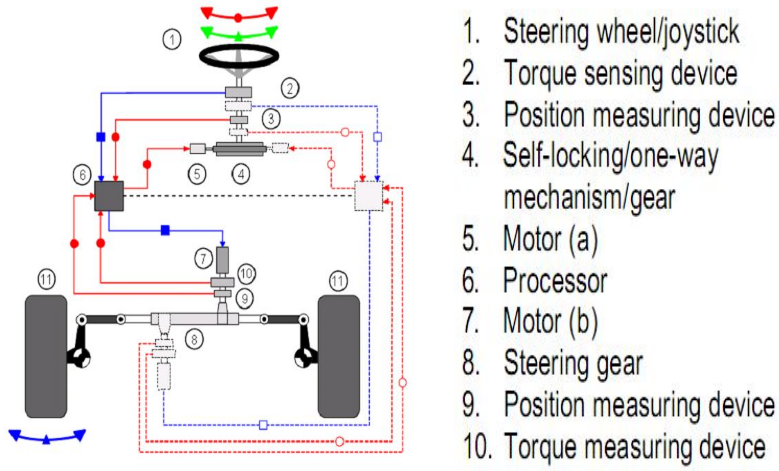



*Fig1.2. Steer by Wire System Components*

### 1.3. Description of System:[12]

The steering wheel is attached to a self-locking mechanism/gear. Between the steering wheel and the self-locking mechanism/gear, a torque measuring device and a position measuring device is mounted. An electric or hydraulic motor (a) is attached to the self-locking mechanism/gear in such a way, that the motor (a) can move the steering wheel freely, but the steering wheel must not be able to move the self-locking mechanism/gear or the motor (a). The position of the steering wheel shall remain fixed unless moved by the motor (a) and must be moveable by motor (a) only.

The torque measuring device, the position measuring device and the electric or hydraulic motor (a) are all connected to a processing unit.

The processing unit are also connected to an electric or hydraulic motor (b) that is connected to a steering gear through a position measuring device and optionally a torque measuring device. The steering gear can be of any type as long as it allows the motor (b) to move the wheels freely and it allows the wheels to move the motor (b) freely as well.

### 1.4. Working Principle:[ 12]

The system basically consists of two separate systems; a control system that enables the driver to control the steerable wheels of the car and a feedback system that allows the driver to sense the reaction of the steerable wheels in the steering wheel.

The torque applied by the driver on the steering wheel is measured by a torque measuring device and transmitted to a processing unit. The processing unit controls a motor (7) to produce a torque corresponding to the torque applied by the driver on the steering wheel. If the torque applied by the motor (7) to the steering gear is sufficient to overcome friction and road forces, the wheels will begin to move. The steering gear can be a traditional rack-and-pinion drive connected to the steered wheels by tie rods.

If external forces acting on the steered wheels exceed the force applied by the tie rods from the torque provided by motor (7) through the steering gear, the wheels will move as well.

The position of the wheels is measured by a position measuring device. Trough the processing unit, the motor (5) is controlled to move the steering wheel through a self-locking mechanism/gear to a position corresponding to the position of the wheels.

The position of the steering wheel is measured by a position measuring device, to provide input information to the processing unit for determining how to control the motor (5) to bring the steering wheel in the correct position.

## 1.5. Motivations:

Hydraulic steering systems have long dominated the industrial utility vehicle market because of their familiarity both to vehicle designers and operators. More recently, a trend has been seen towards the use of electronic steer by- wire systems that provide greater design flexibility by enabling software to customize the connection between the steering wheel and steering mechanism. [9]

Embedded electronics, and more precisely embedded software, is a fast growing area, and software-based systems are increasingly replacing the mechanical and / or hydraulic ones. The reasons for this evolution are technological as well as economical.
On the one hand, the cost of hardware components is decreasing while their performances and reliability are increasing. On the other hand, electronic technology facilitates the introduction of new functions whose development would be costly, or not even feasible, if using mechanical or hydraulic systems alone.[4]

***Moving away from hydraulic Steering*** [9]

Hydraulic steering technology has been used in industrial utility vehicles for decades. Engineers are familiar with its ruggedness in unfriendly environments, and its power density which enhances performance in the most difficult applications. But recent trends in the industry position hydraulic steering as less advantageous for many industrial utility vehicles. Hydraulic steering systems require a motor, pump, valves, hoses and fittings. Utility vehicles that utilize hydraulic drives for other functions may or may not have a hydraulic pump with enough capacity to accommodate the steering system. There has been a general trend away from hydraulics in other applications as well.
Many manufacturers are looking to cut back or eliminate the use of hydraulics, so it is becoming much harder to find spare capacity on a hydraulic pump for the steering system. If spare capacity is not available then it becomes necessary to add a hydraulic system dedicated to steering which substantially raises the cost of this approach. Electronic steer-by-wire systems, on the other hand, are completely self-contained and do not require external pumps or hoses.

This means that they are usually considerably less expensive than hydraulic steering when the cost of the pump, valve, hoses and fittings are taken into account. Another reason for considering a move away from hydraulic steering is the desire to improve battery life of electric powered vehicles and reduce energy consumption of fossil-fuel powered vehicles. Hydraulic vehicles tend to consume relatively high amounts of power because the hydraulic system continually consumes supply power whether or not the steering system is being operated. Electronic steering also consumes considerably less power because power is drawn only when operating the steering systems.
Another reason for the trend away from hydraulic steering is substantial performance improvements that have been made in electric motors in recently years. The power density of electric motors has substantially increased because of advances in magnetic materials, lead/ball screw efficiency, construction, manufacturing techniques and electronics. Today's electric motors can deliver substantially more power while maintaining high levels of efficiency. Steer-by-wire systems have also benefitted by the improved reliability of all electronic and electrical products.

Electronic steering systems provide nearly maintenance free operation and are thus much less prone to fail due to lack of maintenance. Electronic steering also offers substantially greater design flexibility than hydraulic or direct drive systems. There is much greater flexibility in locating the steering wheel because it no longer has to connect directly to a mechanical drive shaft or a hydraulic valve which in turn needs to be connected by hoses to the steering motor.

Electronic steering also provides far more opportunity in configuring the steering functionality of the vehicle. Design engineers themselves can easily change the steering ratio with a software command and can even design the vehicle so that the steering ratio can be changed in the field or programmed to change on the fly depending on vehicle operating conditions. For example, an electronic steering system could be configured to have a high steering ratio at low speeds and a lower ratio at high speeds to help avoid sudden turns at high speed, or configured to allow for rapid maneuvering at low speed. Electronic steering can be programmed to indicate that the vehicle is nearing the end of the steering range by increasing torque resistance. Electronic steering also opens up the door to other more advanced options such as using torque resistance to prevent the operator from steering towards detected obstacles. [9]

### *1.6.Other Advantages of electronic steer-by-wire systems:*

- No steering column – Simplify the design of a car’s interior, giving the driver more space as well as better safety in case of a crash (no intrusion of the steering column). [2]
- The absence of steering shaft and gear reduction mechanism allows much better utilization of the engine’s compartment. [2]
- Decreases the total weight of the car issuing better energy reduction effectiveness. [2]
- Easier implementation of left or right-hand driving. [2]
- No noise or vibration can reach the driver’s hands. [2]
- The most significant benefit is the ability to electronically augment the driver’s steering input depending of drive’s conditions, also called active steering.[2]
- Portable & Easily Manipulated.[7]
- Down the road, steer-by-wire systems will be able to detect imminent collisions, take over the controls and whisk the car away from another speeding vehicle.[5]
- In steer by wire system, a conventional servo power steering is assisted by an electric motor to adjust the front wheels steering angle in proportion to the vehicles current speed. This affords a higher comfort in driving.[1]
- Because hydraulic systems will no longer be necessary in the future and the electronic devices are shrunk more and more, the packaging density can be higher. The producer hope to reduce production costs using new devices. Another main reason for developing new solutions is that many new functions could be integrated.[1]
- SBW systems offer several advantages such as lager space in the cabin, freedom in car interior design, no oil leaking, and less injury in case of car accidents.[15]
- Disabled people and the elderly will benefit immensely from steer-by-wire because they will be able to situate the steering wheel to meet special needs. Traction control systems are very closely tied with driving safety and they can be enhanced with steer-by-wire vastly. For instance, if the car starts sliding and the driver loses control of the car, steering into the wrong side, the system could interfere and take over controls. Very sudden changes in steering could also be avoided with such a system.[3]

- Increase front impact safety.[13]
- New possibilities for vehicle control:[13]
  - Lane keeping assistance.
  - Change handling dynamics.

## *1.7.Challenges:*

- A challenge for the engineers is the realization of a fall-back solution in fault case. Currently all steer-by-wire systems, rather called active steering systems, have a mechanical backup solution implemented. Single electronic systems can not ensure a conditional probability of failure less than 10-7 faults in one hour, which mechanical solutions can achieve. In case of steer-by-wire systems a minimum requirement is the unlimited steer ability of the car. This can be achieved in two ways. The system can be fault-tolerant or fail-safe.

Normally failsafe systems consist of mechanical or hydraulic backup solutions, such as the electro hydraulic brake. Here the electronic subsystems will be shut down in critical failure case and the backup components take their functions over. For this purpose fault detection and diagnosis mechanism have to be implemented. Real x-by-wire systems have no mechanical or hydraulic fallback possibilities. Therefore devices are designed fault-tolerant and arranged in fault-tolerant units (FTU), which are responsible for a specific part of the overall function. Inside a FTU two ore more FSUs are combined to perform an identical application task. If one FSU fails, the function of the superior FTU is not affected by the failure in general. Possibly, in a worst case the performance could be influenced.[1]

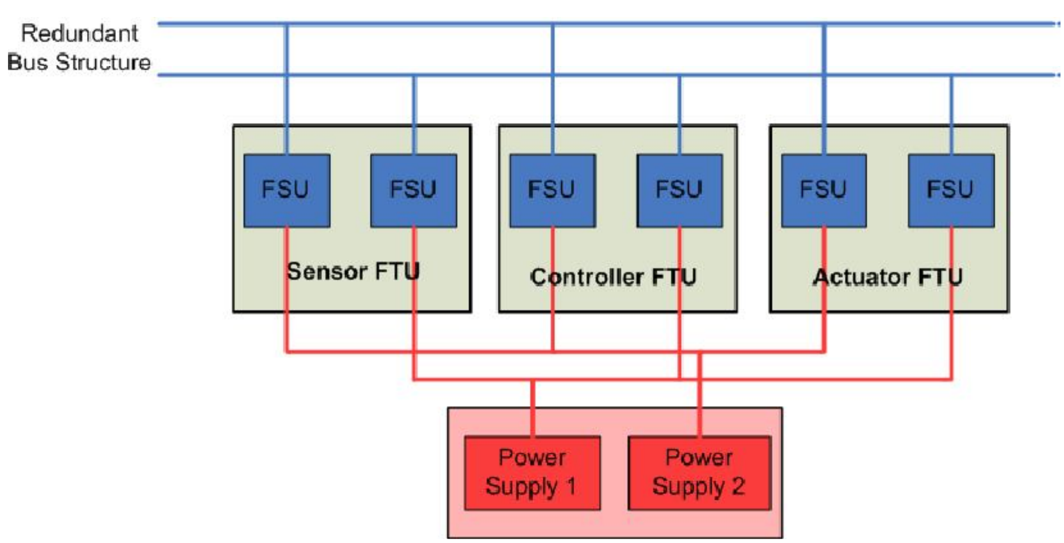



*Fig 1.3.Fall Back solution realization*

- There is a risk that an errant computer would interfere with a driver, who is trying to avoid hitting a pedestrian, warn some experts. Automakers insist that they will test the computers for utmost reliability before letting them hit the roads.[5]
- A critical consideration in moving to electronic steering is that operators are used to the tactile response, or “feel,” provided by both direct mechanical and hydraulic steering systems. The earliest generations of electronic steer-by-wire systems did not provide this feedback and they did not achieve acceptance by vehicle users. [9]
- Another obstacle is that the customer’s demand is not very great at the moment; he does not realize the technical advantages and only sees a higher price tag. But, the advantages of this technology can be very attractive for carmakers. [9]
- Among the drawbacks, the electrical power needed to action the front axle requires the use of 42 Volt technology. At the SAE Conference in 2003, it was said that this technology would not be mature before 2010. This announcement has considerably reduced the emphasis put on the X-by-Wire developments in general. Consequently, 42 Volt technology has to be mature before X-by-Wire systems can be mass produced. Furthermore, the safety issues have not yet been fully defined.[4]
- The size of the X-by-Wire systems and their cost are major constraints for carmakers; electronics-based systems already account for 30% of the total cost in current vehicles.[4]

  In general, for a critical X-by-Wire system, it must be ensured that : [4]

  - A system failure does not lead to a state in which human life, economics or environments are endangered.
  - A single failure of one component must not lead to a failure of the whole X-by-Wire system.

- There are also numbers of disadvantages due to the lack of mechanical connection. For example, the lack of realistic driving feelings, which are the driving feelings for the driver as in conventional steering systems. SBW systems can be out of order because of electrical faults. In addition, the difficulty of the free control of the hand wheel, which is the HW behavior, after the driver’s hands release at certain steered position of the HW. One of the most challenging issues on SBW development is how to give drivers the realistic feelings or realistic force feedback which is the same as conventional hydraulic steering systems. The force feedback for SBW systems has been studied by many researchers.[2m]

- In removing the mechanical link between the steering wheel and the front wheels, steer-by-wire must rely solely on electronics to guarantee safe operation. To be acceptable for the mass market, steer-by-wire has to be at least as safe, if not safer, than a conventional steering system. This means that occurrence of faults in any part of the system should be exceedingly rare, and a fault should never be allowed to turn into a catastrophic failure. [11]

- All components must be highly-reliable, robust, redundant, cheap and miniaturized at the same time.[8]

- Finally, one objective that must be reached is that an X-by-Wire system offers the same availability and the same maintainability as their mechanical/hydraulic counterparts. The challenge is to prove that a given X-by-Wire system adheres to all these requirements.[4]

## *1.8.Background Information:*

Steer-By-Wire already exists in military jets and commercial airplanes.[2]

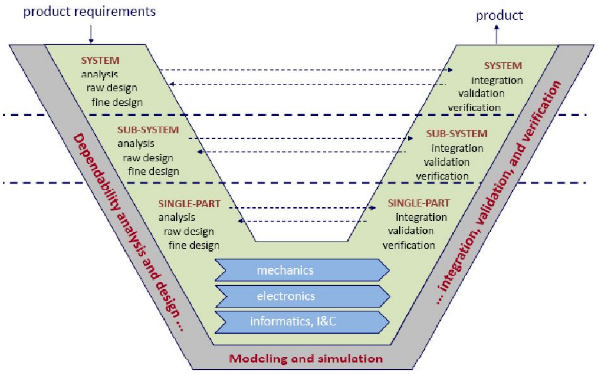
- ***2008:*** Design Concept and Advantages of Steer-by-Wire System.
- ***2008:*** Fault-Tolerant Architecture of Yaw Moment Management with Steer-by-Wire, Active Braking and Driving- Torque Distribution Integrated Control.
- ***2007:*** TTA-Group Steer-by-Wire Working Group: An Initiative to Set up a Reference Architecture for Steer-by-Wire in Off- Highway Industry.
- ***2006:*** Development of a Steer-by-Wire System for the GM Sequel.
- ***2005:*** Electric Actuation Technologies for Automotive Steering Systems.
- ***2004:*** A Control System Methodology for Steer by Wire Systems.
- ***2000:*** Steer-by-Wire as a Mechatronic Implementation.
- ***2000:*** Future Electrical Steering Systems: Realizations with Safety Requirements.
- ***1999:*** Electric Power Steering – The First Step on the Way to "Steer by Wire".
- ***1999:*** The Steer-by-Wire Prototype Implementation: Realizing Time Triggered System Design, Fail Silence Behavior and Active Replication with Fault-Tolerance Support.[10]

BMW introduced Steer-by-Wire in its 2000 prototype BMW Z22 but due to the cost involved, only implements certain components of steer-by-wire technology; they call it Active Steering.[2]

## *1.9. Conclusion:*

One thing that is only needed which is time to apply steer by wire system in all vehicle types. Day by day safety problems are being solved, also trials for introducing this system without mechanical or hydraulic back-up system will succeed one day. Once this has been achieved, legislation for this new system will be more easily than today. Carmakers will accept this system immediately due to its simplicity, reduced cost and advantages that SBW system has.

# Chapter 2




# System Design According to VDI2206

# CHAPTER 2

As we are going to design and implement a mechatronic system, we have moved to VDI 2206 guidelines.

## 2.1.What is VDI 2206?

- VDI (**Verein Deutscher Ingenieure) (**English: Association of German Engineers) is a German organization of engineers and natural scientists.
- VDI 2206 provides a methodology where an intelligent and smart mechatronic product could be designed, manufactured and developed through predefined steps.

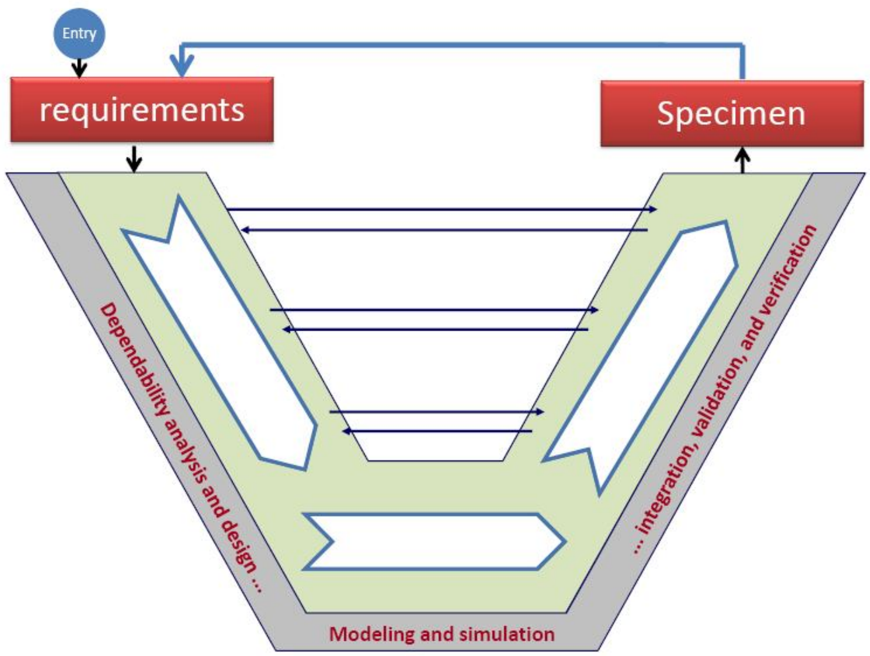



*Fig 2.1.Mechatronics system/product creation cycles according to VDI 2206*

As illustrated in Fig 2.1the cycle starts with a need for a new product/system with specific requirements that must be satisfied.

*In our project the Need is to design and implement a smart system for steering where electrical wires takes place instead of mechanical connections.*

## 2.2. Steering System requirements:

- The system must be functional steering system.
- The safety on the system must be top priority after functionality.
- The system must contain feedback elements so that the error reaches its minimum.
- The system must be easy to modify.
- The system must be easy to add new parts and components.
- The system concepts must apply to any type of car.

*By getting more focus on VDI 2206, we have encountered three major stages:*

- Design stage
- Modeling and Simulation stage
- Integration, Validation and verification stage

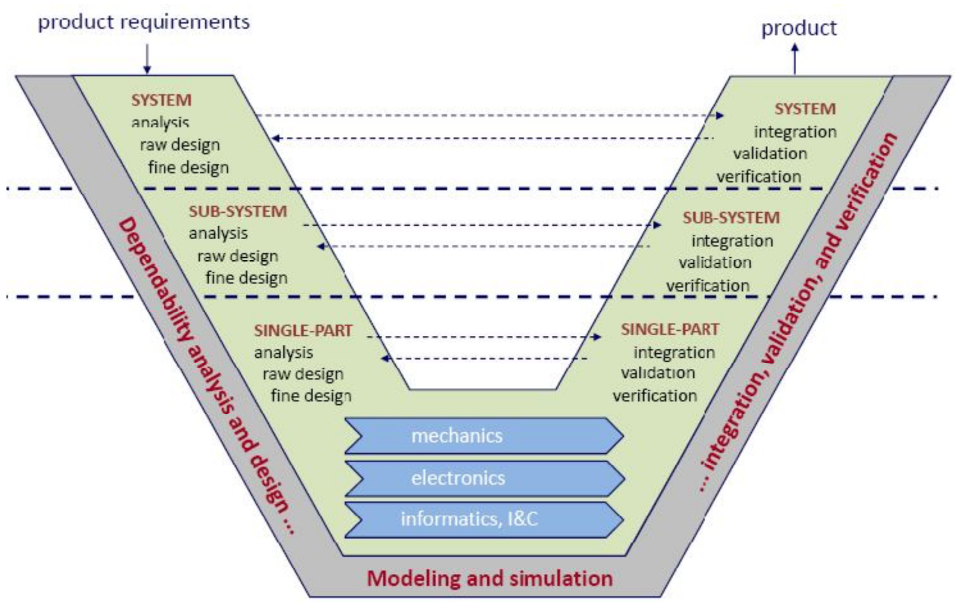



*Fig 2.2.Sub-stages of the Mechatronics product/system creation*

## 2.3. Design stage:

-We began to design our steering system according to the Mechatronics system configuration (inspired with the closed loop control system).

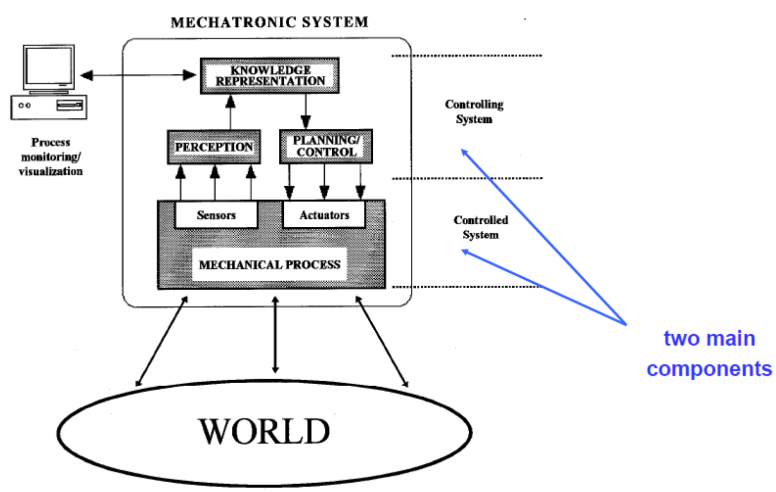



*Fig 2.3.Mechatronics system configuration*

This allows us to our system to sub-modules independent of each other. This means that we separated work between group members for parallel work in the project.

This also means that if one module is malfunctioning, it can be replaced without affecting the whole system. This also makes the maintenance easier.

## ***Module 1:***

## ***2.4. Mechanical system (Test Bed):***

***Requirements:***

- The system must have the functionality of steering system.
- The system must be changeable.
- The system must have the capability to model different cars and different road conditions.
- The system must be as simple as possible.
- Stress requirements.

Based on the requirements we have to choose between three methods of manufacturing of the system, so the design must be compatible with the manufacturing procedure.

1. Casting the whole system.
2. Machining from blocks of metal.
3. Building the system from common steel sections and use welding (Fabrication).

Due to The flexibility of the Fabrication process, its cost, and the availability of the steel sections on the market we have chosen the fabrication process to be the main method of implementation of the mechanical system.

## ***2.5. The friction mechanism:***

-The rule of the friction mechanism is to allow the test of the system in different road conditions and in different car weights.

-Power screw mechanism is sufficient for simulating the different friction conditions, it is also can be modified for automated friction system using dc motor for more test capabilities.

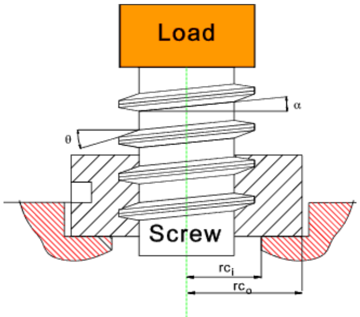



*Fig 2.4.Power screw Mechanism*

## Module 2:

### 2.6. Actuator:

We need an efficient actuator that is capable of steering the wheels instead of mechanical movement transmission (Rack and Pinion). A DC Motor might be a right choice.

*Fig 2.5.DC Motor*

***Advantages*** of a brushed DC motor include low initial cost, high reliability, and simple control of motor speed.

***Disadvantages*** are high maintenance and low life-span for high intensity uses. Maintenance involves regularly replacing the brushes and springs which carry the electric current, as well as cleaning or replacing the commutator.

## Module 3:

### 2.7. Motor Driver:

We need a control circuit that could control the direction of the DC-Motor, so that we could steer our system left and right. We may think about an H-Bridge.

We know that H-bridges are available as integrated circuits, or can be built from discrete components.

We expect that our DC – Motor must has a large stall current due to the huge weight that is going to steer.

Integrated circuits H-Bridges like L 298 cannot resist large current. So we need to design one from discrete components like BJTs, MOSFETS or Relays.

We have chosen MOSFETs and this selection would be explained in chapter 5.

## Module 4:

### 2.8. The input system and the feedback system (Including signal conditioning module):

The input system and the feedback system will be based on incremental encoder as a sensor. The input system will be incremental encoder monitoring the movement of a model of the driving wheel. The feedback sensor will be also incremental encoder monitoring the movement of the actuator or the final control element of our system.

Incremental encoders are used to track motion and can be used to determine position and velocity. This can be either linear or rotary motion. Because the direction can be determined, very accurate measurements can be made.

*Fig 2.6.Incremental Encoder*

## *Module 5:*

### *2.9. Control:*

We will control our system through a microcontroller ***PIC 16F877a.***

***Why Microcontroller?***

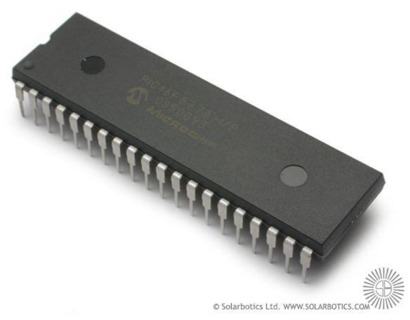


Fig 2.7.PIC 16F877a

Microcontrollers are used in automatically controlled products and devices, such as automobile engine control systems, implantable medical devices, remote controls, office machines, appliances, power tools, and toys. By reducing the size and cost compared to a design that uses a separate microprocessor, memory, and input/output devices, microcontrollers make it economical to digitally control even more devices and processes.

### *Remarks:*

- We may need to make special circuits to connect the electrical modules together.
- We may need special mechanical connections to connect the actuator and the mechanical system, also the encoders.

### *2.10. Modeling and Simulation Stage:*

- In Chapter 4 we have modeled and simulated the mechanical test bed (Module1) through INVENTOR Program.
- In Chapter 5 we have modeled and simulated the motor along with H-Bridge (Module 2&3) using Proteus Program.
- In Chapter 6 we have modeled and simulated the control circuit as well as incremental encoders (Modules 4&5) using the latter program.

### *2.11. Integration, Verification and Validation Stage:*

*Factors we must look into while this stage of the system:*

- System performance
- System failure and safety
- Test results

In this step in the process of creating the Mechatronics product/system we have to go through a down to top steps of judgment on the components of the system, and the system as whole.

If any requirement of the system isn't fit, then we have to return to the design stage and modify the main design to fit our requirements in the next macro-cycle.

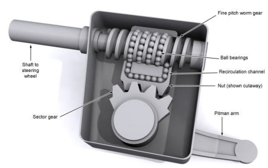
After passing through these cycles we will have a working product/system.

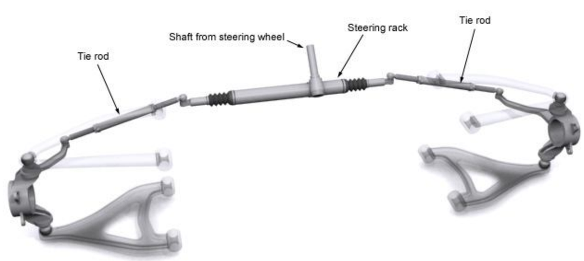
At this point we have to decide of weather we need further modification on our product/system or not, and this decision will be based on the time factor, the cost factor and the field of application of our product/system.

***Remark:***

*Chapter 7* deals with the integration, Verification and Validation of our system.

# Chapter 3


# Steering System Designs

# CHAPTER 3

Before going on to know steering system designs, we have to be more familiar with steering system components.

Like most things in a car, the concept of steering is simple - you turn the steering wheel, the front wheels turn accordingly, and the car changes direction.

## 3.1. Basic steering components:[16]

Nearly 99% of the world's car steering systems are made up of the same three or four components. The steering wheel, which connects to the steering system, which connects to the track rod, which connects to the tie rods, which connect to the steering arms. All the designs essentially move the track rod left-to-right across the car. The tie rods connect to the ends of the track rod with ball and socket joints, and then to the ends of the steering arms, also with ball and socket joints. The purpose of the tie rods is to allow suspension movement as well as an element of adjustability in the steering geometry. The tie rod lengths can normally be changed to achieve these different geometries.

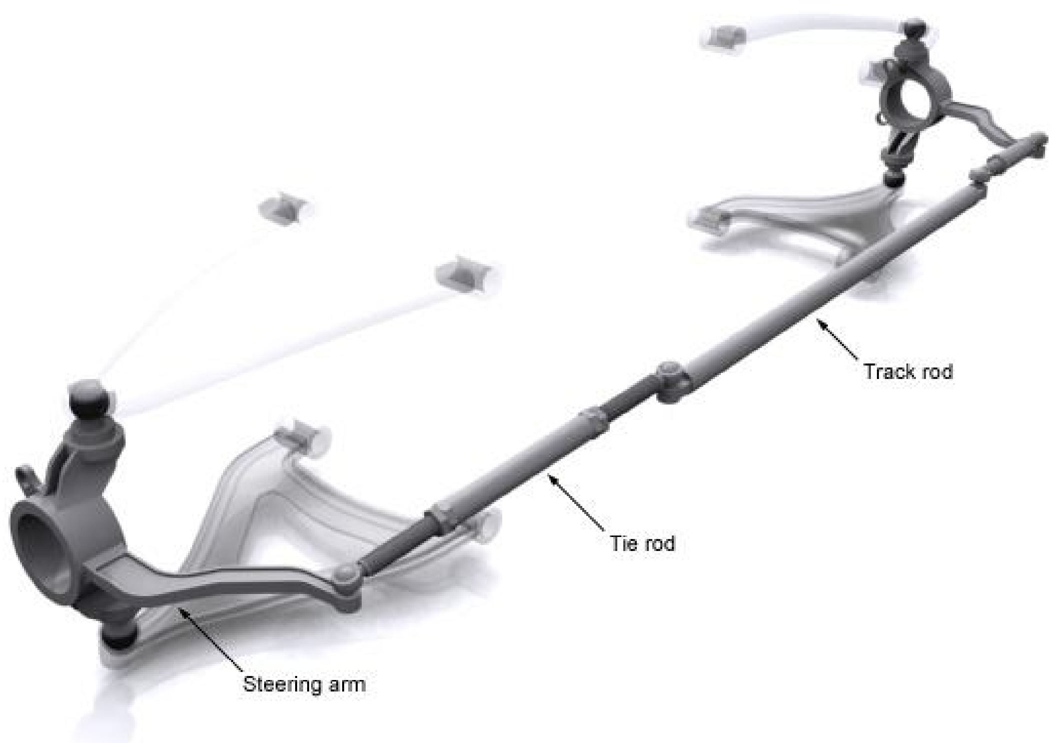



*Figure 3.1.Basic steering system components*

### *3.2. The Ackermann Angle : your wheels don't point the same direction*

When a car goes around a corner, the outside wheels travel further than the inside wheels, in the case of steering, you need the front wheels to actually point in different directions.

This is the diagram from the Transmission Bible. You can see the inside wheels travel around a circle with a smaller radius (r2) than the outside wheels (r1):

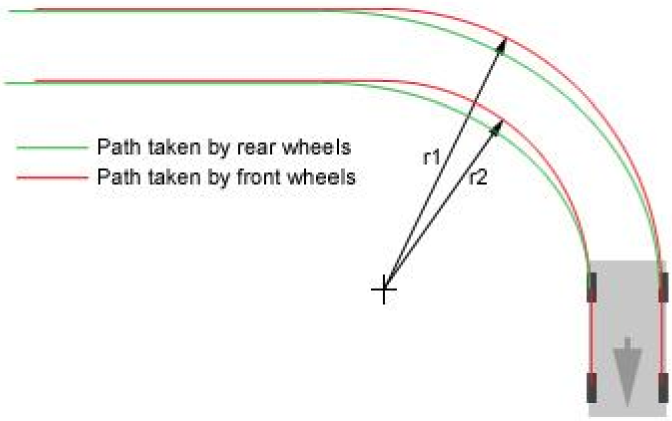



*Figure 3.2.Ackermann Angle*

In order for that to happen without causing undue stress to the front wheels and tyres, they must point at slightly different angles to the centre line of the car. The following diagram shows the same thing only zoomed in to show the relative angles of the tyres to the car. It's all to do with the geometry of circles:

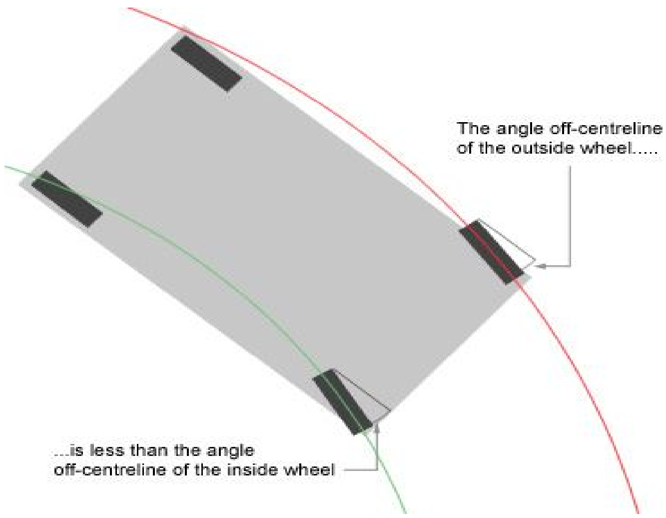



*Figure 3.3.Zoomed view*

This difference of angle is achieved with a relatively simple arrangement of steering components to create a trapezoid geometry (a parallelogram with one of the parallel sides shorter than the other). Once this is achieved, the wheels point at different angles as the steering geometry is moved.

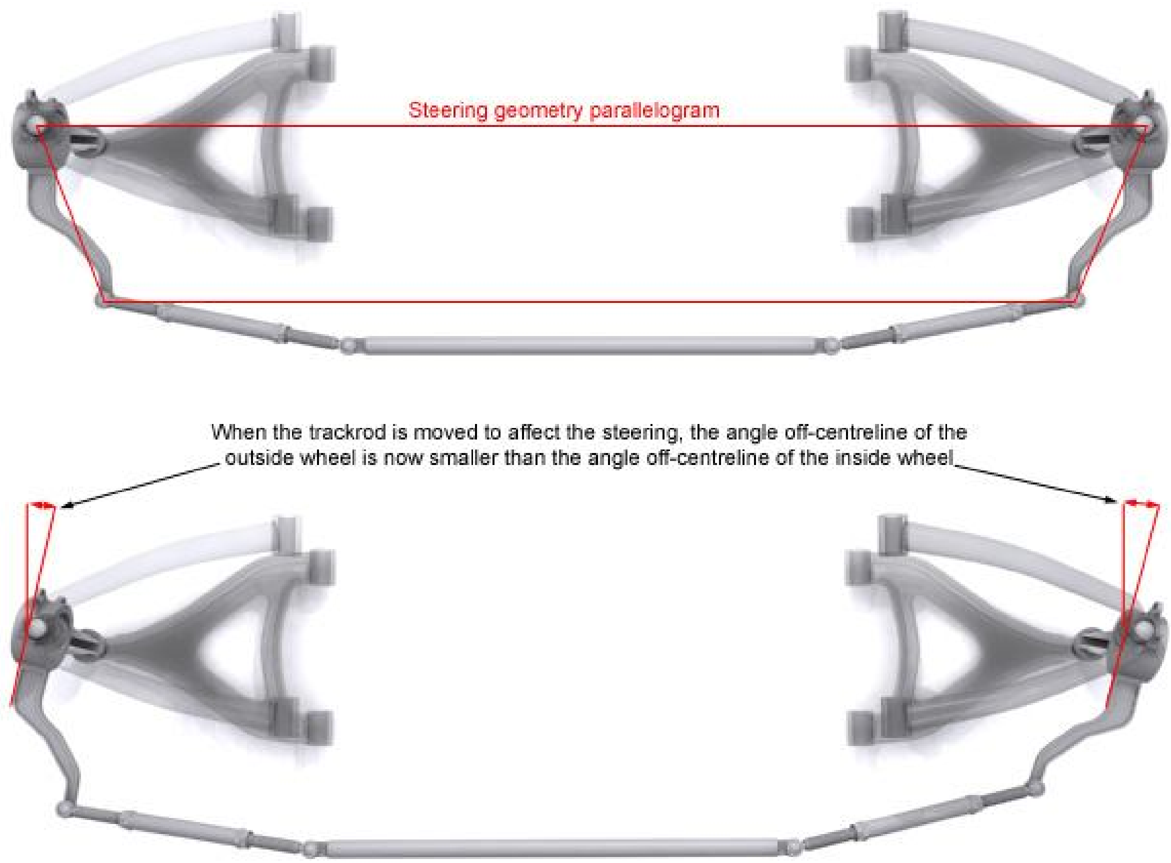



*Figure 3.4.Steering system arrangement*

## 3.3. Steering ratios:

Every vehicle has a steering ratio inherent in the design. If it didn't you'd never be able to turn the wheels. Steering ratio gives mechanical advantage to the driver, allowing you to turn the tyres with the weight of the whole car sitting on them, but more importantly, it means you don't have to turn the steering wheel a ridiculous number of times to get the wheels to move. Steering ratio is the ratio of the number of degrees turned at the steering wheel vs. the number of degrees the front wheels are deflected. So for example, if you turn the steering wheel 20° and the front wheels only turn 1°, that gives a steering ratio of 20:1. For most modern cars, the steering ratio is between 12:1 and 20:1. This, coupled with the maximum angle of deflection of the wheels gives the lock-to-lock turns for the steering wheel. For example, if a car has a steering ratio of 18:1 and the front wheels have a maximum deflection of 25°, then at 25°, the steering wheel has turned

25°x18, which is 450°. That's only to one side, so the entire steering goes from -25° to plus 25° giving a lock-to-lock angle at the steering wheel of 900°, or 2.5 turns (900° / 360).
This works the other way around too of course. If you know the lock-to-lock turns and the steering ratio, you can figure out the wheel deflection. For example if a car is advertised as having a 16:1 steering ratio and 3 turns lock-to-lock, then the steering wheel can turn 1.5x360° (540°) each way. At a ratio of 16:1 that means the front wheels deflect by 33.75° each way.

For racing cars, the steering ratio is normally much smaller than for passenger cars - ie. closer to 1:1 - as the racing drivers need to get fuller deflection into the steering as quickly as possible.

### *3.4. Steering System designs:*

There really are only two basic categories of steering system today; those that have pitman arms with a steering 'box' and those that don't. Older cars and some current trucks use pitman arms.

#### 1) *Pitman arm:*

Pitman arm mechanisms have a steering 'box' where the shaft from the steering wheel comes in and a lever arm comes out - the pitman arm. This pitman arm is linked to the track rod or centre link, which is supported by idler arms. The tie rods connect to the track rod. There are a large number of variations of the actual mechanical linkage from direct-link where the pitman arm is connected directly to the track rod, to compound linkages where it is connected to one end of the steering system or the track rod via other rods. The example below shows a compound link.

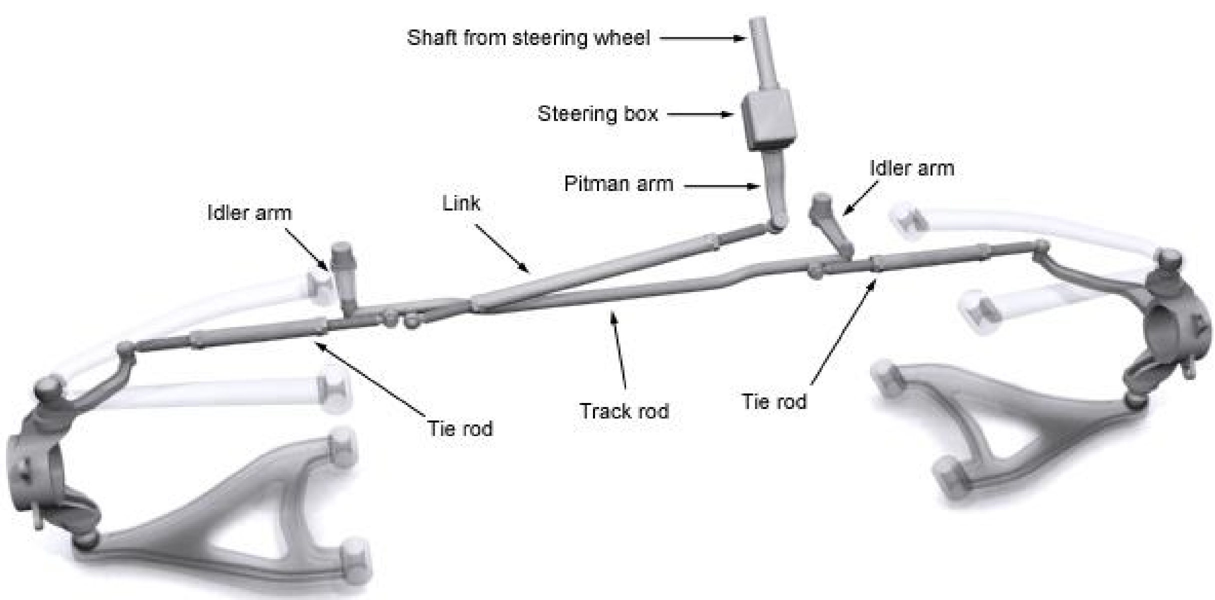



*Figure 3.5.Pitman arm*

Most of the steering box mechanisms that drive the pitman arm have a 'dead spot' in the centre of the steering where you can turn the steering wheel a slight amount before the front wheels start to turn. This slack can normally be adjusted with a screw mechanism but it can't ever be eliminated. The traditional advantage of these systems is that they give bigger mechanical advantage and thus work well on heavier vehicles.

The following are the four basic types of steering box used in pitman arm systems:

- **Worm and sector**

In this type of steering box, the end of the shaft from the steering wheel has a worm gear attached to it. It meshes directly with a sector gear (so called because it's a section of a full gear wheel). When the steering wheel is turned, the shaft turns the worm gear, and the sector gear pivots around its axis as its teeth are moved along the worm gear. The sector gear is mounted on the cross shaft which passes through the steering box and out the bottom where it is splined, and the the pitman arm is attached to the splines. When the sector gear turns, it turns the cross shaft, which turns the pitman arm, giving the output motion that is fed into the mechanical linkage on the track rod. The following diagram shows the active components that are present inside the worm and sector steering box. The box itself is sealed and filled with grease.


*Figure 3.6.Worm and Sector*

### Worm and roller

The worm and roller steering box is similar in design to the worm and sector box. The difference here is that instead of having a sector gear that meshes with the worm gear, there is a roller instead. The roller is mounted on a roller bearing shaft and is held captive on the end of the cross shaft. As the worm gear turns, the roller is forced to move along it but because it is held captive on the cross shaft, it twists the cross shaft. Typically in these designs, the worm gear is actually an hourglass shape so that it is wider at the ends. Without the hourglass shape, the roller might disengage from it at the extents of its travel.

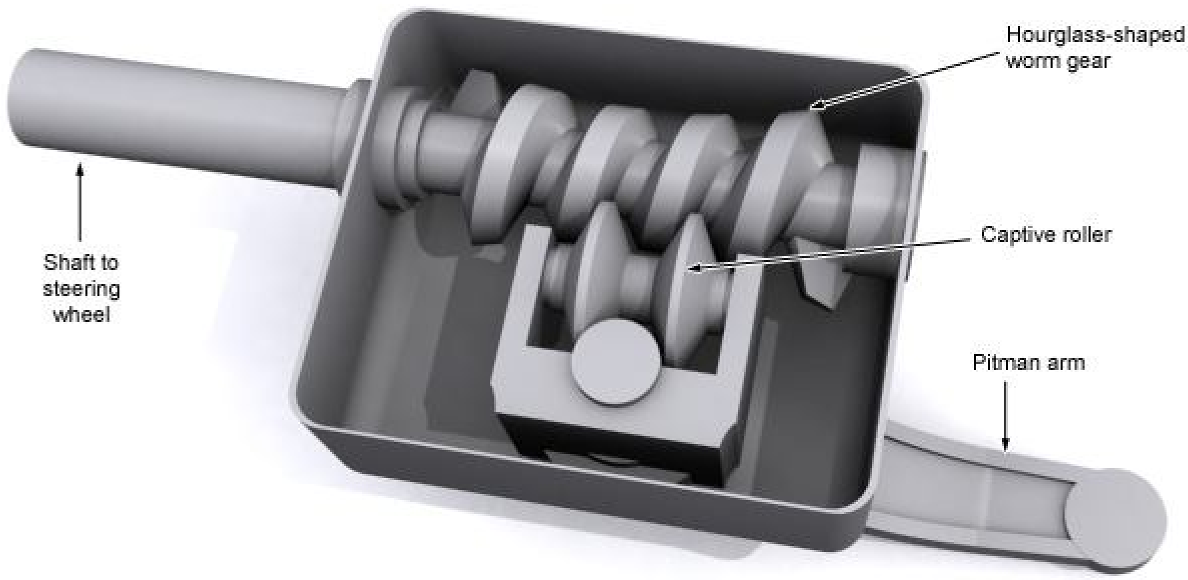



*Figure 3.7.Worm and roller*

### Worm and nut or re-circulating ball

This is by far the most common type of steering box for pitman arm systems. In a recirculating ball steering box, the worm drive has many more turns on it with a finer pitch. A box or nut is clamped over the worm drive that contains dozens of ball bearings. These loop around the worm drive and then out into a recirculating channel within the nut where they are fed back into the worm drive again. Hence recirculating. As the steering wheel is turned, the worm drive turns and forces the ball bearings to press against the channel inside the nut. This forces the nut to move along the worm drive. The nut itself has a couple of gear teeth cast into the outside of it and these mesh with the teeth on a sector gear which is attached to the cross shaft just like in the worm and sector mechanism. This system has much less free play or slack in it than the other designs, hence why it's used the most. The example below shows a recirculating ball mechanism with the nut shown in cutaway so you can see the ball bearings and the recirculation channel.

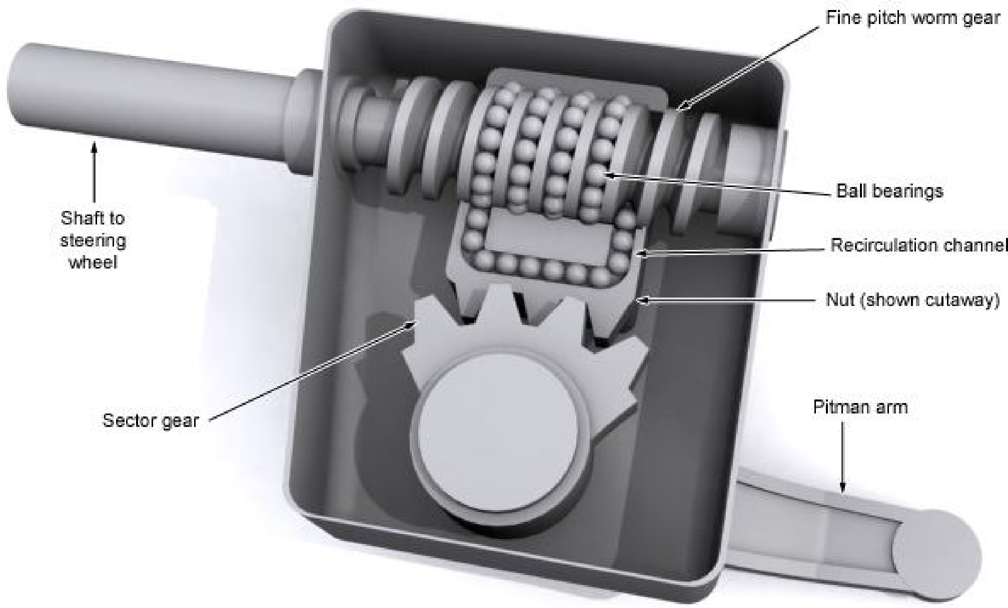



*Figure 3.8.Worm and nut or re-circulating ball*

### Cam and lever

Cam and lever steering boxes are very similar to worm and sector steering boxes. The worm drive is known as a cam and has a much shallower pitch and the sector gear is replaced with two studs that sit in the cam channels. As the worm gear is turned, the studs slide along the cam channels which forces the cross shaft to rotate, turning the pitman arm. One of the design features of this style is that it turns the cross shaft 90° to the normal so it exits through the side of the steering box instead of the bottom. This can result in a very compact design when necessary.


*Figure 3.9.Cam and lever*

### 2) Rack and pinion

This is by far the most common type of steering you'll find in any car today due to it's relative simplicity and low cost. Rack and pinion systems give a much better feel for the driver, and there isn't the slop or slack associated with steering box pitman arm type systems. The downside is that unlike those systems, rack and pinion designs have no adjustability in them, so once they wear beyond a certain mechanical tolerance, they need replacing completely. This is rare though. In a rack and pinion system, the track rod is replaced with the steering rack which is a long, toothed bar with the tie rods attached to each end. On the end of the steering shaft there is a simple pinion gear that meshes with the rack. When you turn the steering wheel, the pinion gear turns, and moves the rack from left to right. Changing the size of the pinion gear alters the steering ratio. It really is that simple. The diagram below shows an example rack and pinion system as well as a close-up cutaway of the steering rack itself.

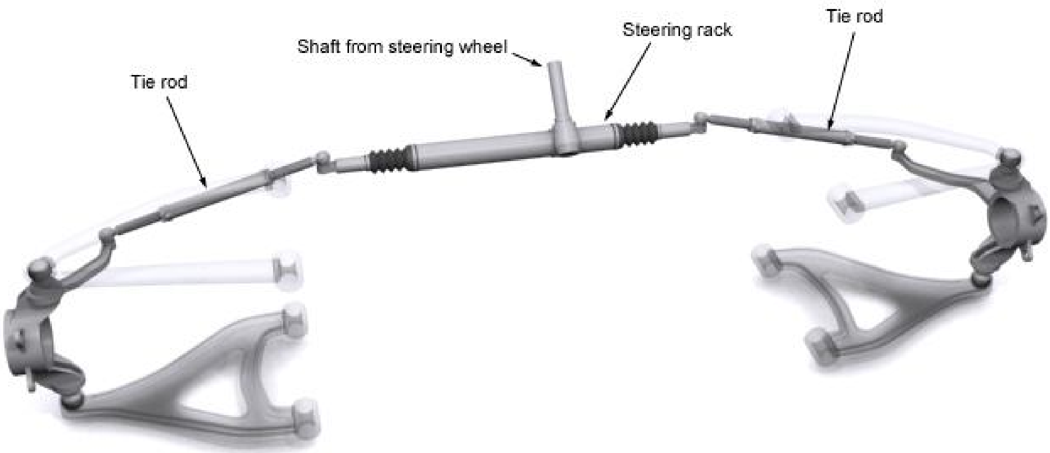



*Figure 3.10.Rack and Pinion System*


*Figure 3.11. Cam and lever*

## 3.5 Rack and Pinion system Components:[17]

- Rubber bellows

This rubber bellows is attached to the Rack and Pinion housing. It protects the inner joints from dirt and contaminants. In addition, it retains the grease lubricant inside the rack and pinion housing. There is an identical bellows on the other end of the rack for the opposite side connection.

- Pinion

The pinion is connected to the steering column. As the driver turns the steering wheel, the forces are transferred to the pinion and it then causes the rack to move in either direction. This is achieved by having the pinion in constant mesh with the rack.

- Rack

The rack slides in the housing and is moved by the action of the meshed pinion into the teeth of the rack. It normally has an adjustable bush opposite the pinion to control their meshing, and a nylon bush at the other end.

- Inner ball joint or socket

The inner ball joint is attached to the tie-rod, to allow for suspension movement and slight changes in steering angles.

- Tie-rod

A tie rod end is attached to the tie-rod shaft. These pivot as the rack is extended or retracted when the vehicle is negotiating turns. Some tie-rods and tie-rod ends are left or right hand threaded.

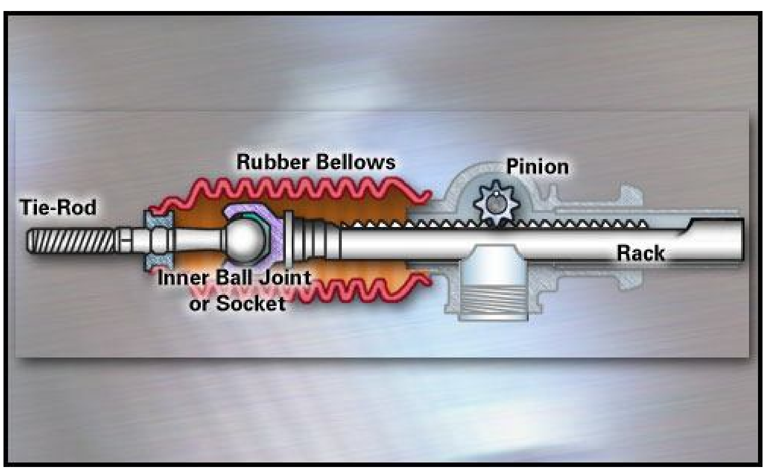



*Figure 3.12 Rack and Pinion system Components*

## *3.6. Steering System Selection:*

*As we have found that the most spreading system in automotive is Rack and Pinion system, so it was our selection to model and test a steer by wire system.*

*And this system is discussed in depth in the next chapter.*

# Chapter 4

# Mechanical Test Bed

# CHAPTER 4

## 4.1. Introduction:

Our purpose in this chapter is to reach applicable and reliable design for real steering system of real car taking into consideration minimum requirements for safety and comfort of the driver. We will give the priority to the cost and the simplicity of the system so we will try throughout this chapter to find the best fit design that satisfy our needs to simulate the real steering mechanical system as a first step then develop it to reach our target which is SBW system.

## 4.2. Mechanical Design steps:

1. Selecting and purchasing full steering system as mentioned in the previous chapter
2. Extract the dimensions from that system
3. Make chassis design (Test bed) for the system using Inventor program
4. Stress calculations
5. Searching for design parts needed in market (El-SABTIA)
6. Editing our design according to standard parts in the market
7. Purchasing parts of edited design and all needed components
8. Implementation and assembly of the System
9. Test the system from mechanical side and add some improvements to make the system more efficient

## 4.3. Taking Dimensions and CAD drawings:

As mentioned in mechanical design steps the second step of design procedure is to extract the dimensions from real steering system so as to convert the system to CAD drawings and create 3D model for the system as a first step to design a chassis according to real steering system dimensions on the Computer which can be edit or modify easily and more efficient instead of implementation of chassis hardware directly which is very hard and cost to modify.

Extracting dimensions:

We extract the dimensions from the real steering system using 3 main tools as shown in fig.4.1. :

a. Digital Vernier
b. 2 types of Meters
c. Rule

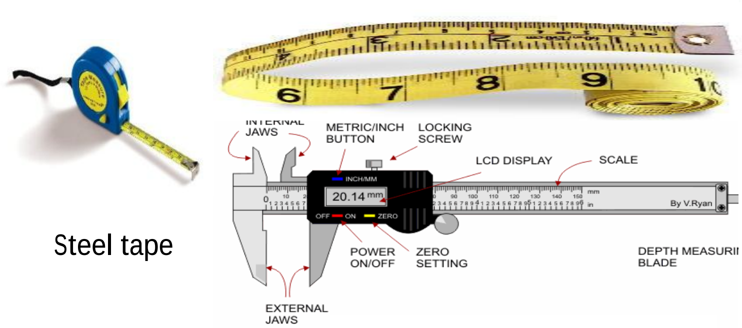


Fig.4.1. Measurement tools

We used digital Vernier to ensure the level of accuracy of measuring diameter, length and depth. But Vernier become less efficient with long diameters or lengths so in this case we replace the Vernier by meter or rule. Using pervious procedure of measuring enabled us to take accurate dimensions as much as possible.

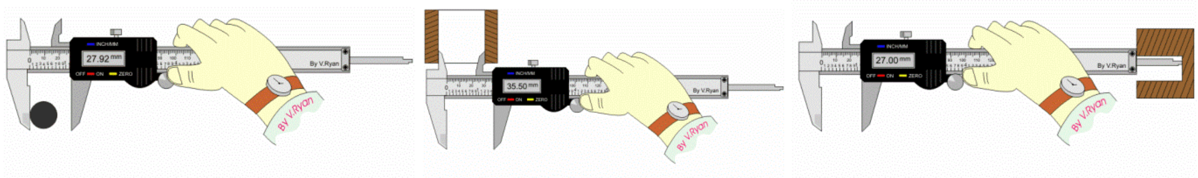


*Fig.4.2 Different Vernier positions for diameter, length and depth measurements*

## 4.4. Mechanical parts of SBW divided into 2 parts:

### 1. Steering system

Based on cost principle we choose used steering system but it satisfy our needs as it has high accuracy very small backlash and almost no mechanical errors.

### 2. Chassis (test bed)

Our chassis is **designed from scratch** without depending on previous chassis designs so it's won't be familiar when you see it for the first time but it's very practical and sufficient.

### 4.4.1. Steering system components:

### 1. Steering rack & Pinion

Steering rack is belonging to old **Fiat 128** car and it's used part but it works very well without backlash so it satisfy our required sensitivity without problems.

*Fig.4.3. Real Steering rack*

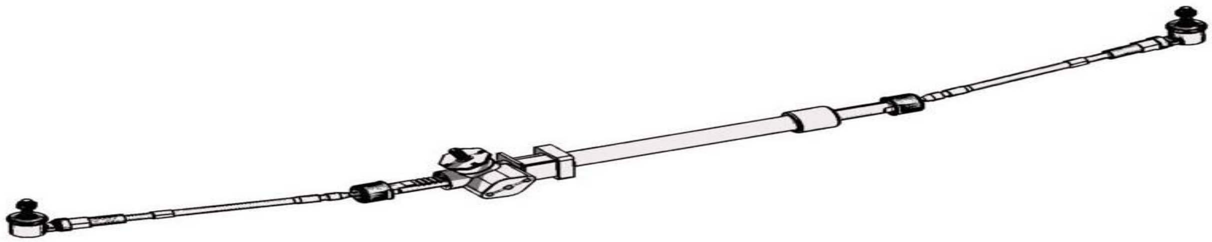


*Fig.4.4. 3D Model of Steering rack*

### 2. *Drum brakes and Control arms*

These parts are belonging to old **Sahin** car and also it's used and performs its functions very well.

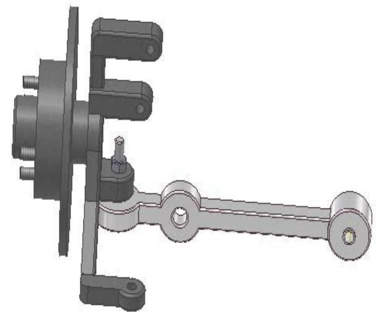


*Fig.4.5.drum front view* *Fig.4.6.drum back view* *Fig.4.7.drum 3D model*

### 3. *Two Car Wheels*

These two car wheel are belonging to old Sahin car and its used wheels but it works well.

*Fig.4.8.wheel front view*
*Fig.4.9. wheel back view* *Fig.4.10. wheel 3D model*

### 4.4.2. Chassis (Test bed)

We try to use standard components with same size as much as possible to achieve these two important factors:

a) *Simple design*
b) *Minimum cost*

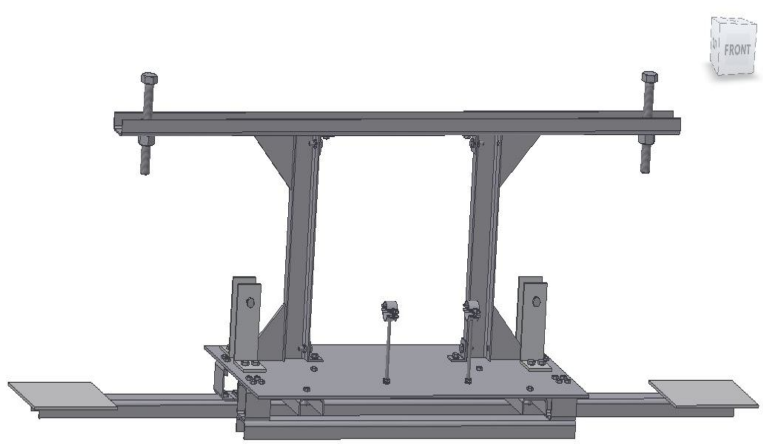



*Fig.4.11. Chassis (Test bed) 3D inventor model*

And this is clear in our component selection, for example we use 1 standard size for C channel (60*30*3) with different lengths and we use it in different positions to obtain different functions as shown in fig below.

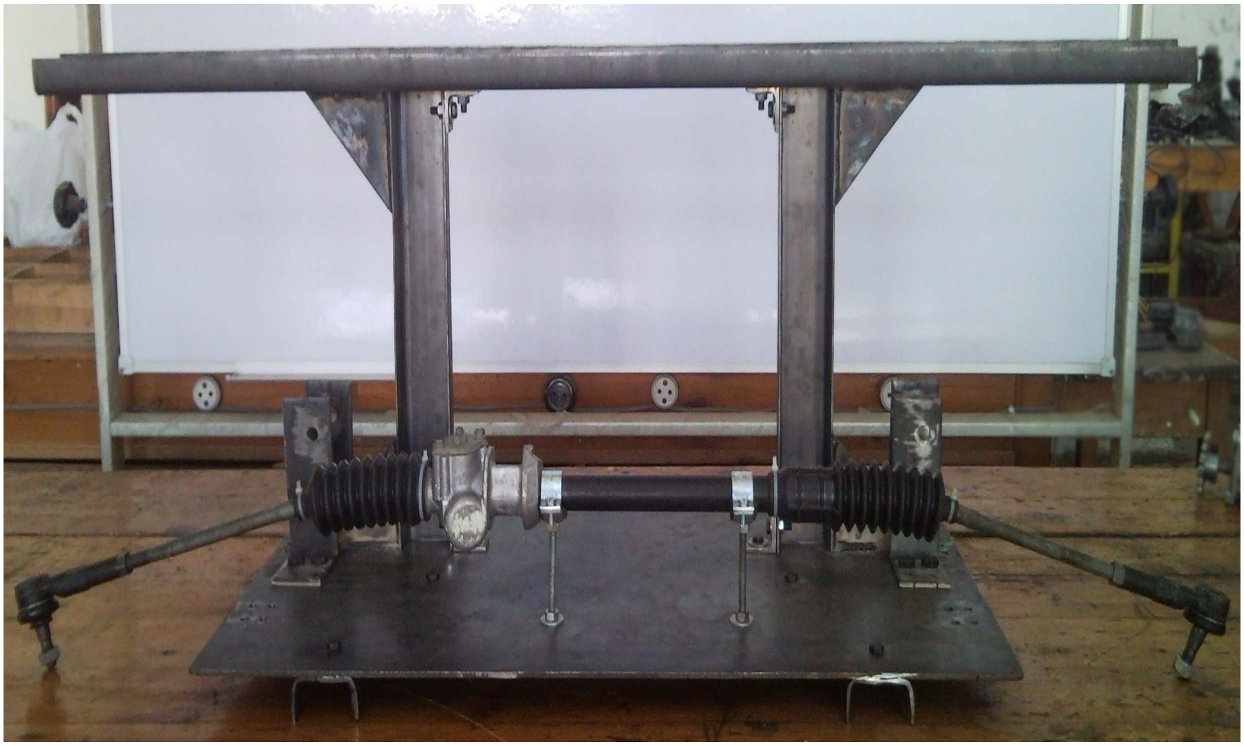


*Fig.4.12. real chassis (test bed) mechanism*

## Components of test bed chassis:

### a. C channel (60*30*3)

1. (1) Upper C channel: 1350 mm length

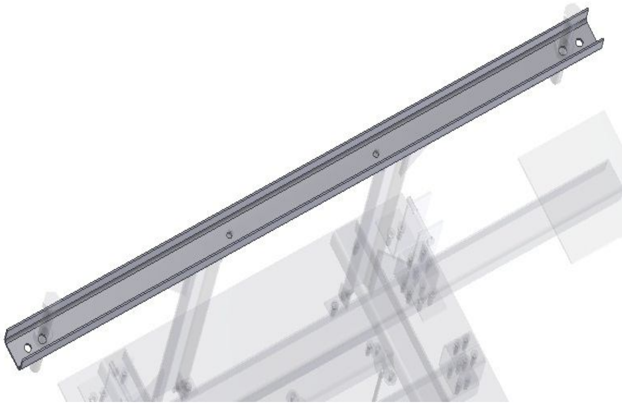


*Fig.4.13. Upper C – 1350 mm (Real – 3D model)*

<u>*2. (2) C channels supporting upper one: 400*2=800 mm length*</u>

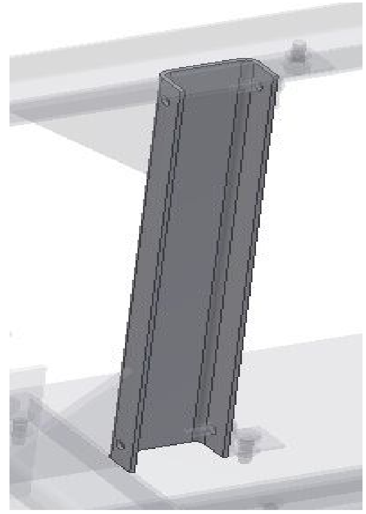



*Fig.4.14. C channels supporting upper one (Real – 3D model)*

<u>*3. (2) 400mm C channels (web for base plate): 400*2=800 mm length*</u>

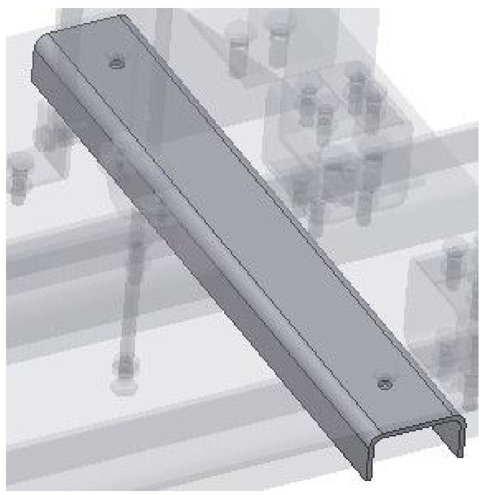


*Fig.4.15. 400mm C channel webs (Real – 3D model)*

<u>*4. (1) horizontal C channel (web for base plate): 480 mm length*</u>

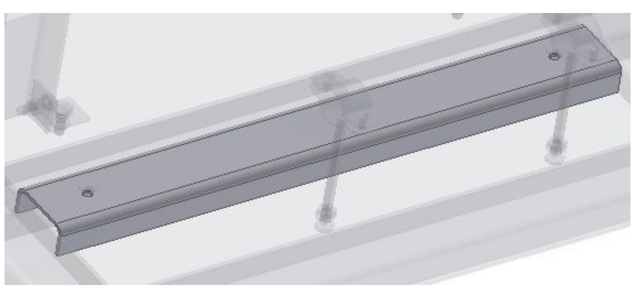


*Fig.4.16. 4800mm C channel web (Real – 3D model)*

*5. (16) small C channel for raising the base plate: 60*16 = 960 mm length*

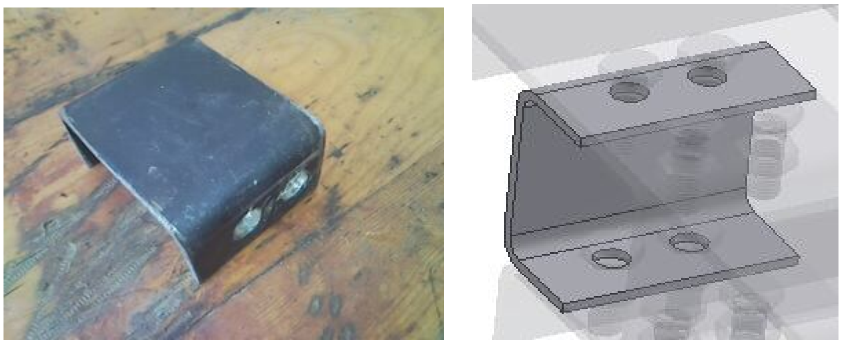


*Fig.4.17. small C (Real – 3D model)*

*6. (1) lower (Under the wheels) C channel: 1680 mm length*

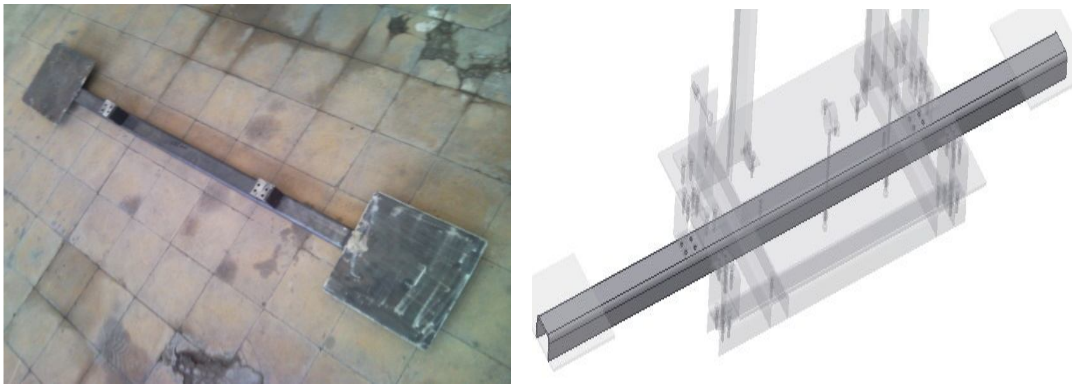


*Fig.4.18. Under the wheels C channel (Real – 3D model)*

*7. (1) lower C channel (base for the system): 800 mm length*

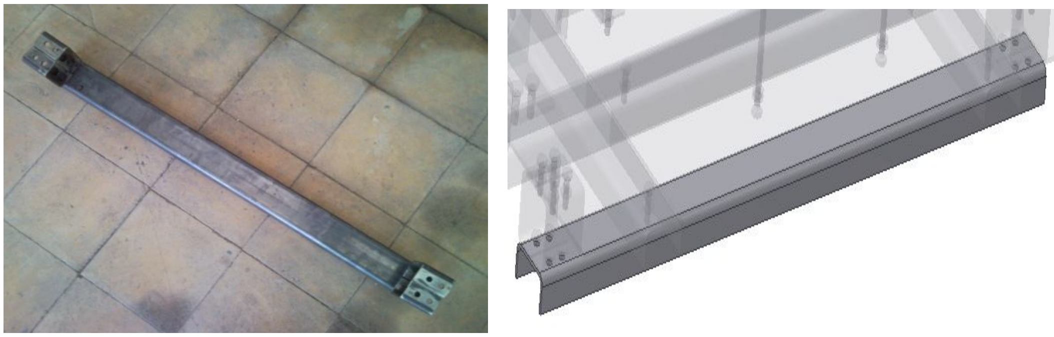


*Fig.4.19. Under the wheels C channel (Real – 3D model)*

C channel total length needed = 1350+800+800+480+960+1680+800 = 6870 mm ~ 7 m

(7) Meter C channel can be divided into:

1. 6m (Standard C channel bar length)
2. 1m (Non standard C channel bar length)

## *b. Plates*

*1. Main plate (1m*0.5m*5mm-thickness)*

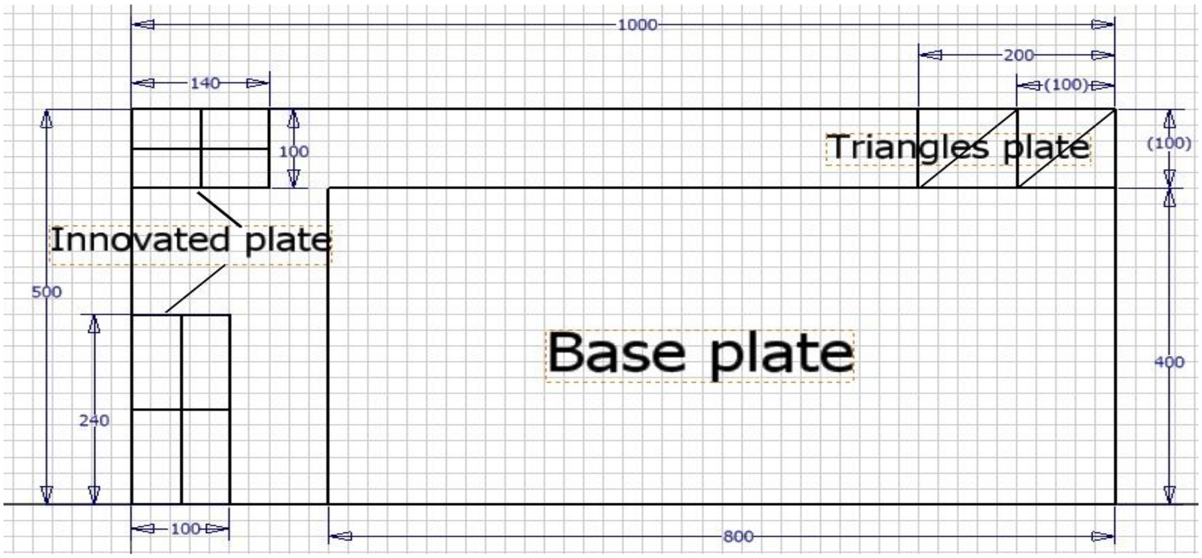



*Fig.4.20. Main plate division*

*1.1. Base plate (80cm*40cm*5mm-thickness)*

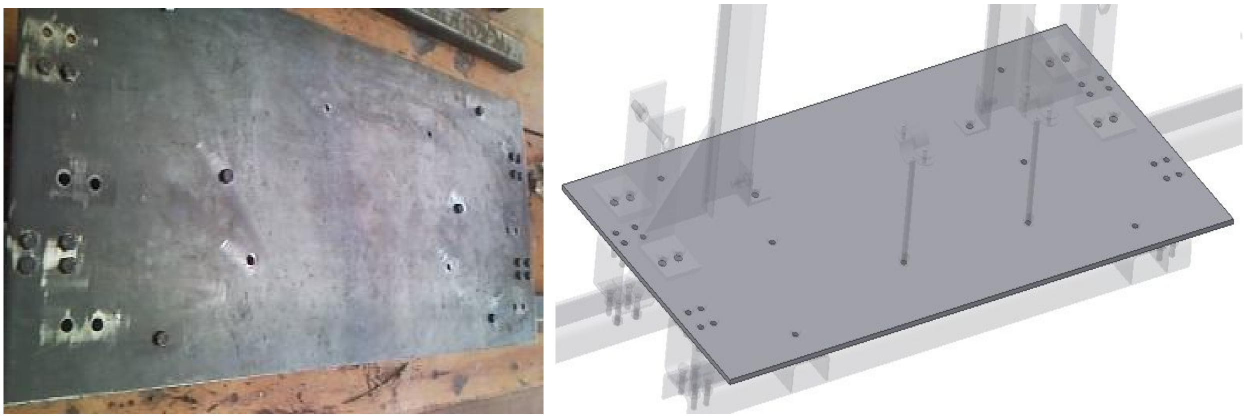


*Fig.4.21. Base plate (Real – 3D model)*

*1.2. Web plate (20cm*10cm*5mm-thickness)*

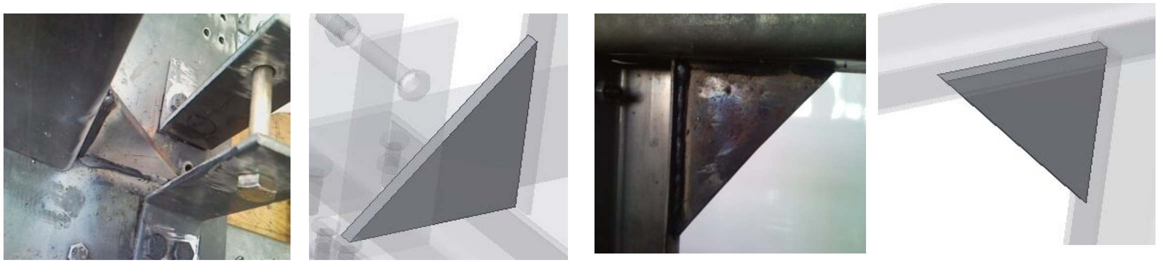


*Fig.4.22. Base plate (Real – 3D model)*

*1.3. Innovated part plate1 (24cm*10cm*5mm-thickness)*

*1.4. Innovated part plate2 (14cm*10cm*5mm-thickness)*

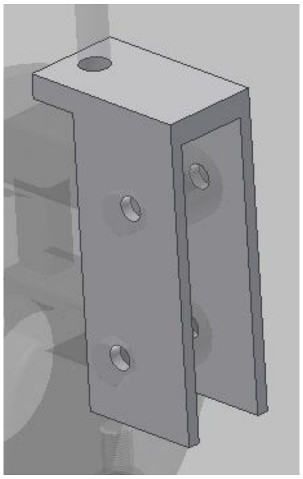


*Fig.4.23. Innovated Part (Real – 3D model)*

*3. Under the tires plate (30cm*30cm*2mm-thickness)*

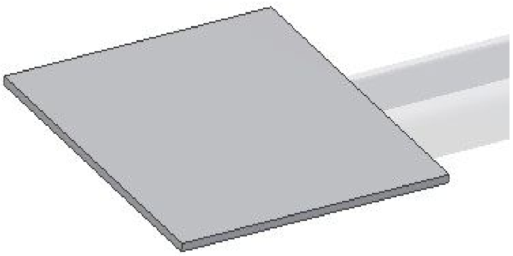
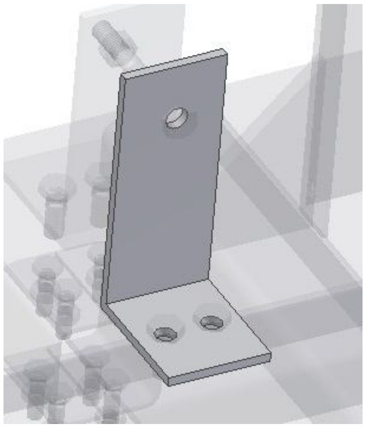


*Fig.4.24. Under tires plate (Real – 3D model)*

## *c. Individual Parts:*

*1. 4*L (14cm (height)*7cm (width)*5cm (length)*5mm-thickness)*

*Fig.4.25. Under tires plate (Real – 3D model)*



*2. 4 angles (35mm*35mm*5mm-thickness)*

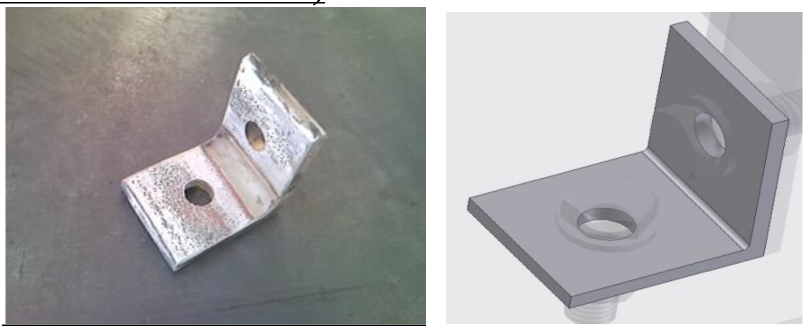


*Fig.4.26. angle (Real – 3D model)*

*3. 2 clamps to hold steering rack*

*Fig.4.27. Rack clamp (Real – 3D model)*

*4. Bolts, Washers and Nuts*

4.1. 62 bolts (M8-25mm-length)
4.2. 62 nuts (M8)
4.3. 8 bolts (M10-25mm-length)
4.4. 4 bolts (M10-50mm-length)
4.5. 12 nuts (M10)
4.6. 2 bolts (M12-80mm-length)
4.7. 2 bolts (M12-150mm-length)
4.8. 6 nuts (M12)
4.9. 2 bolt (M22-16cm-length)
4.10. 4 nuts (M22)
4.11. 2 bolts (M8-10cm-length) for the clamp
4.12. 4 nuts (M8) for the clamp
4.13. 8 washers (M8)
4.14. 4 washers (M12)
4.15. 8 bolts (M12) for wheels
4.16. 8 nuts (M12) for wheels

*Fig.4.28. Bolts and Nuts*

*5. Tension – Compression Mechanism (Friction Mechanism)*

*Fig.4.29. Friction Mechanism*

Although that we mentioned in Chapter 2 that we will use a power screw as a friction mechanism, we have replaced it by this new part as we found that it is more simple and easier to attach to our system and satisfy our needs properly.

## 4.5. Mechanical Operations and Finishing:

### 4.5.1. Machining

#### 4.5.1.a.Cutting

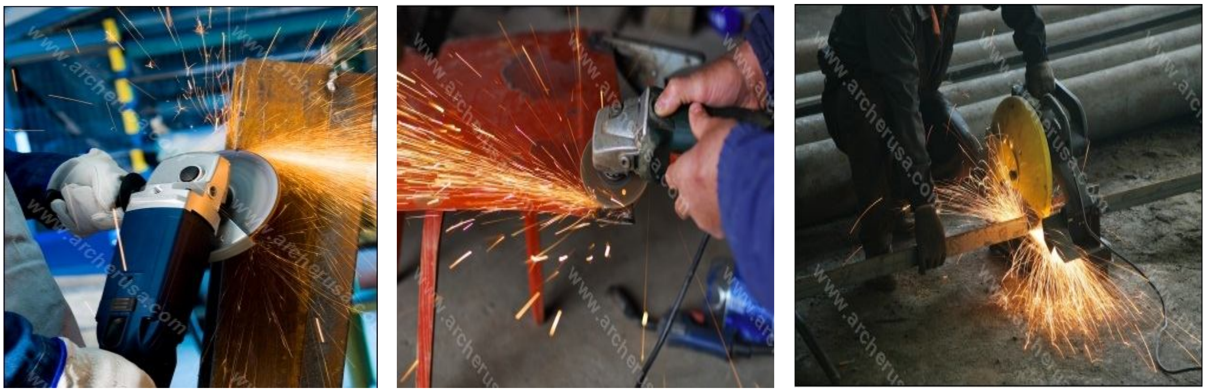


*Fig.4.30. Cutting operation*

Cutting is the first step in our mechanical chassis as we use cutting in all C channel cutting and used also for metal plate cutting. After cutting, another machining operations may be done like drilling or grinding or welding etc. also we can use the tool of cutting to remove the edges result from other operations like electrical cutting as shown above.

#### 4.5.1.b. Drilling

Drilling is the main operation in our mechanical operations because of its plentiful and repeatability.

Drilling also it is very important operations as its accuracy affect the assembly operation directly unlike grinding for example.

*Fig.4.31. Drilling operation*

#### 4.5.1.c.Grinding

Grinding is a not main operation but it's important for safety and for assembly as it is defined as cutting and refining the edges results from different cutting operations.

*Fig.4.32. Grinding operation*

### 4.5.2. Welding

We try to avoid welding as possible and use bolts and nuts instead so as to be capable of parting off parts again (if we need) but sometimes welding become essential for rigidity and strength of the system or when using bolts is not practical (no place to find the bolt and it's nut) so we use welding in some positions in our system as shown in fig. in two main positions:

1. (4) supporting triangles

2. Innovated parts

*Fig.4.33. supporting triangle*

*Fig.4.34. Innovated part*

### 4.5.3 Real Mechanical Chassis Assembly:

*Fig.4.35. Assembly Configuration*

Fig.4.36. Assembly Configurayion

## 4.5.4. Cleaning and Painting:

Afterwards the test bed was painted with two colours, blue for the lower part and black for the upper one as the next images shows

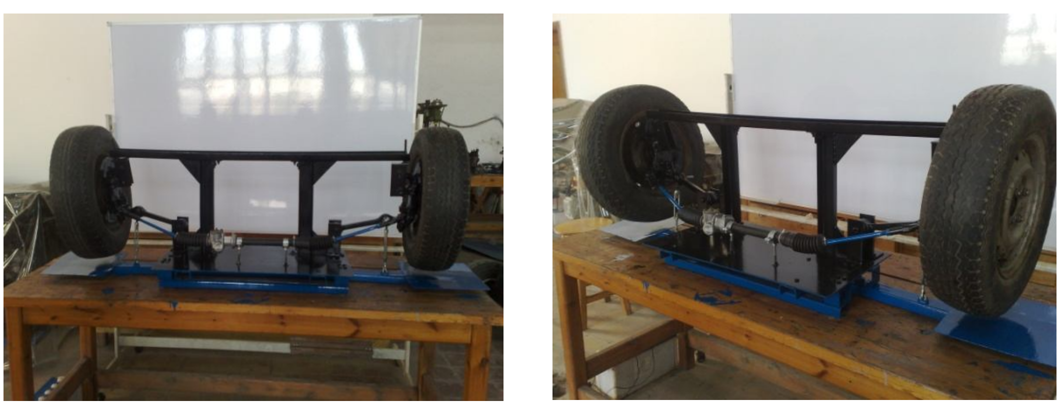


Fig 4.37.Test Bed after painting

## 4.6. Stress Calculations:

### 1. Upper C channel calculations using enhanced module in inventor program.

⊞ **Project Info**

⊟ **Material**

| | | |
|---|---|---|
| Material | | Steel |
| Yield Strength | $S_y$ | 300 MPa |
| Modulus of Elasticity | E | 206000 MPa |
| Modulus of Rigidity | G | 80000 MPa |

⊟ **Beam Calculation**

⊟ **Calculation Properties**

| Include | | | |
|---|---|---|---|
| Yes | Density | ρ | 7860 kg/m^3 |
| Yes | Shear Displacement Ratio | β | 0.000 ul |
| | Number of Divisions | | 1000 ul |
| | Mode of reduced stress | | HMH |

⊟ **Loads**

| Index | Location | Radial Force | | | | Bending Moment | | | | Continuous Load | | | | | Axial Force | Torque | Deflection | | | | Deflection Angle |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Y | X | Size | Direction | Y | X | Size | Direction | Y | X | Size | Direction | Length | | | Y | X | Size | Direction | |
| F1 | 0 mm | -300.000 N | | -300.000 N | | | | | | | | | | | | | 506.694 microm | | 506.694 microm | | 0.08 deg |
| q1 | 0 mm | | | | | | | | | 0.030 N/mm | | 0.030 N/mm | | 1350.000 mm | | | 506.694 microm | | 506.694 microm | | 0.08 deg |
| | 1350 mm | | | | | | | | | | | | | | | | 506.694 microm | | 506.694 microm | | 0.08 deg |
| F2 | 1350 mm | -300.000 N | | -300.000 N | | | | | | | | | | | | | 506.694 microm | | 506.694 microm | | 0.08 deg |

⊟ **Supports**

| Index | Type | Location | Reaction Force | | | | | Yielding | | Radial Displacement | | Deflection | | | | Deflection Angle |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Y | X | Size | Direction | Axial Force | Y | X | Y | X | Y | X | Size | Direction | |
| 1 | Free | 405 mm | -261.956 N | | 261.956 N | 180.00 deg | | | | | | 0.000 microm | | 0.000 microm | | 0.05 deg |
| 2 | Fixed | 945 mm | -261.956 N | | 261.956 N | 180.00 deg | | | | | | 0.000 microm | | 0.000 microm | | 0.05 deg |

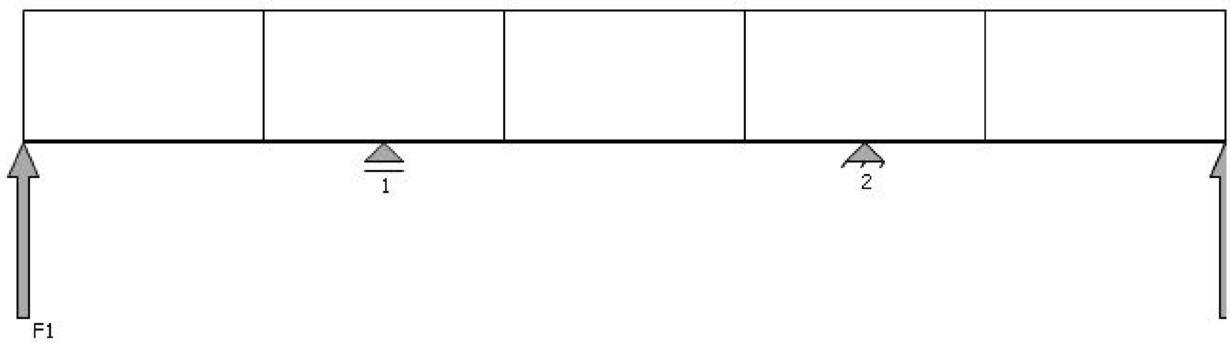
⊟ **Supports**

| Index | Type | Location | Reaction Force | | | | | Yielding | | Radial Displacement | | Deflection | | | | Deflection Angle |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Y | X | Size | Direction | Axial Force | Y | X | Y | X | Y | X | Size | Direction | |
| 1 | Free | 405 mm | -261.956 N | | 261.956 N | 180.00 deg | | | | | | 0.000 microm | | 0.000 microm | | 0.05 deg |
| 2 | Fixed | 945 mm | -261.956 N | | 261.956 N | 180.00 deg | | | | | | 0.000 microm | | 0.000 microm | | 0.05 deg |

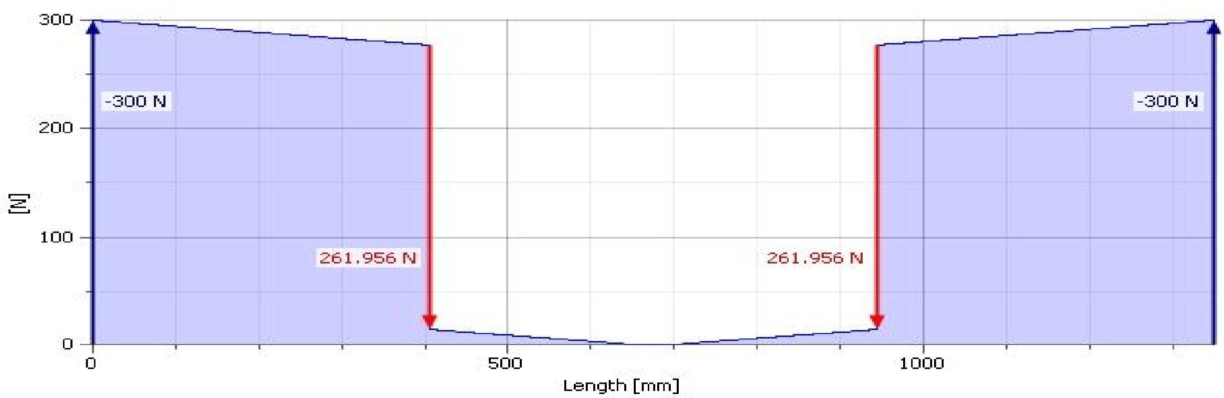

⊟ **Results**

| | | |
|---|---|---|
| Length | L | 1350.000 mm |
| Mass | Mass | 3.629 kg |
| Maximal Bending Stress | $\sigma_B$ | 19.213 MPa |
| Maximal Shear Stress | $\tau_S$ | 0.877 MPa |
| Maximal Torsional Stress | $\tau$ | 0.000 MPa |
| Maximal Tension Stress | $\sigma_T$ | 0.000 MPa |
| Maximal Reduced Stress | $\sigma_{red}$ | 19.213 MPa |
| Maximal Deflection | $f_{max}$ | 506.694 microm |
| Angle of Twist | $\varphi$ | 0.00 deg |

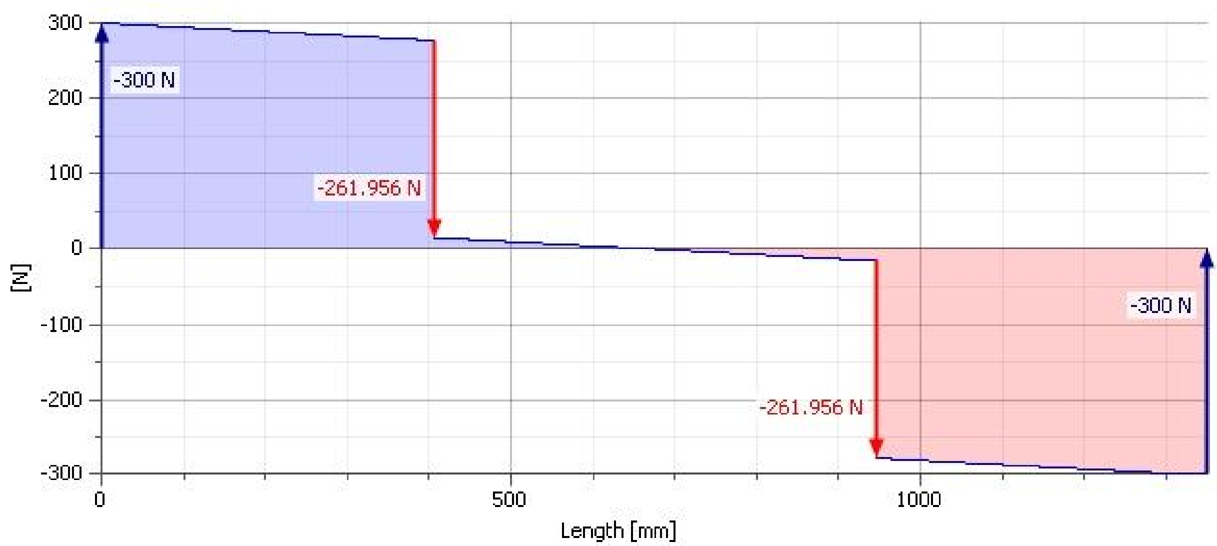
Preview



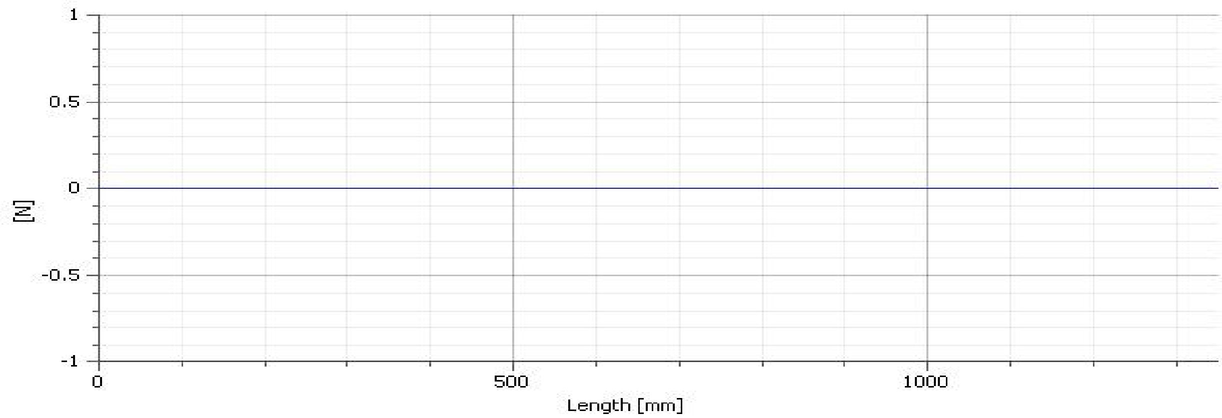

Shear Force



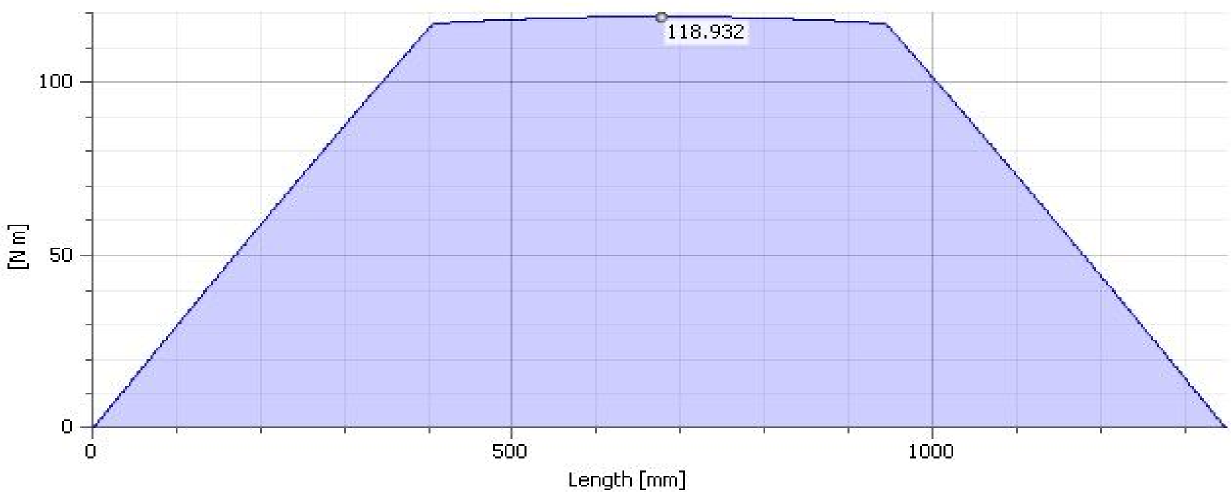

Shear Force, YZ Plane



**Shear Force, XZ Plane**

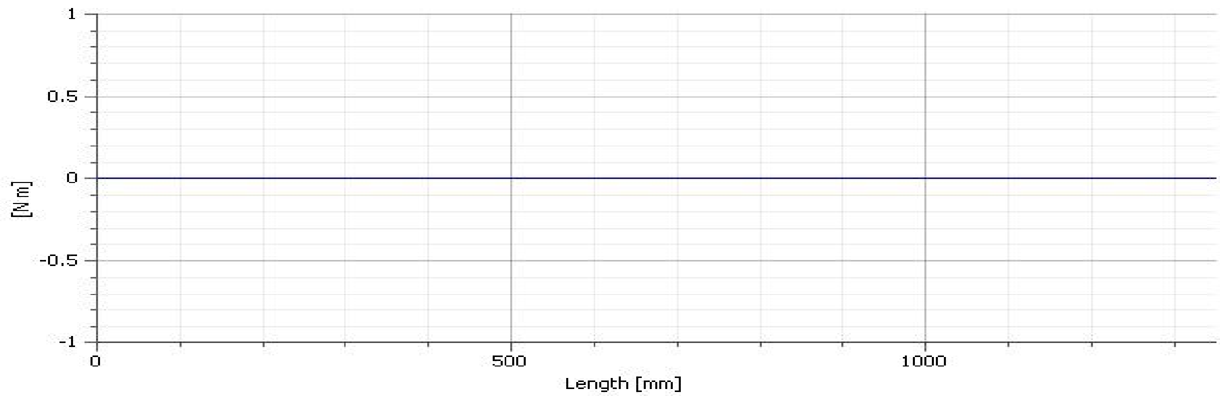



**Bending Moment**

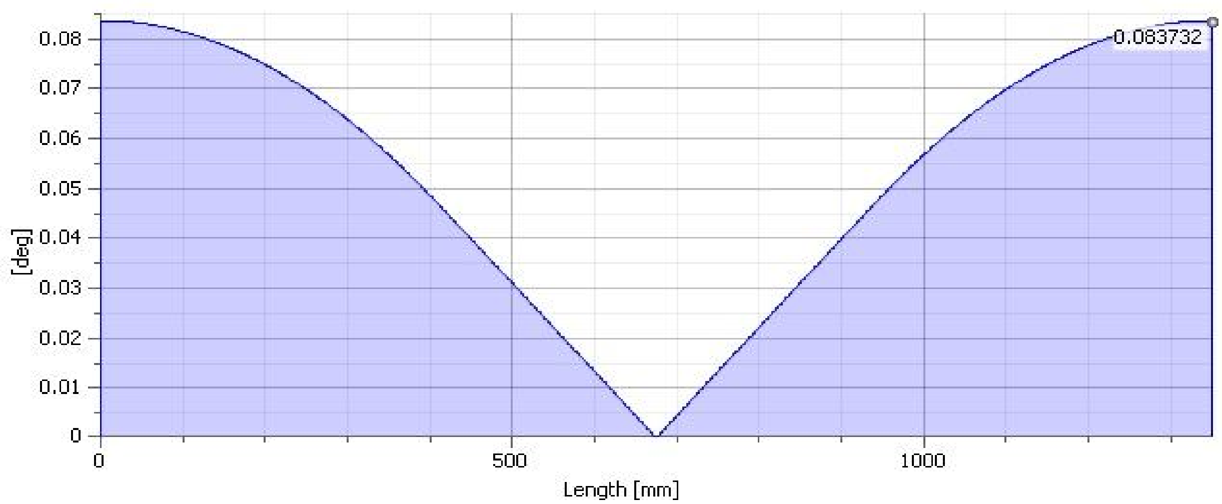



**Bending Moment, YZ Plane**

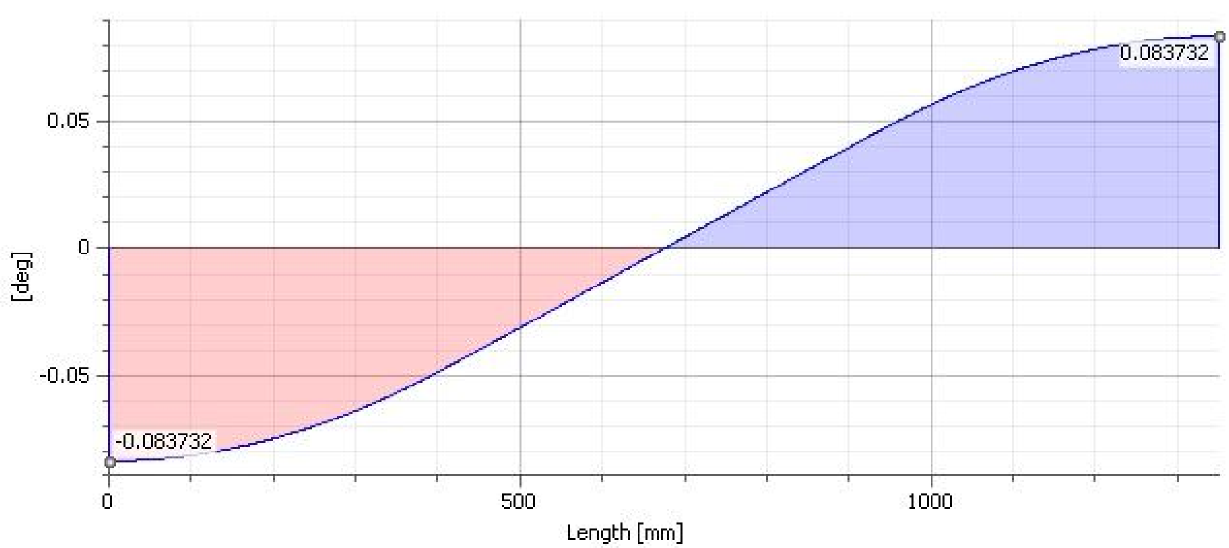
⊟ **Bending Moment, XZ Plane**



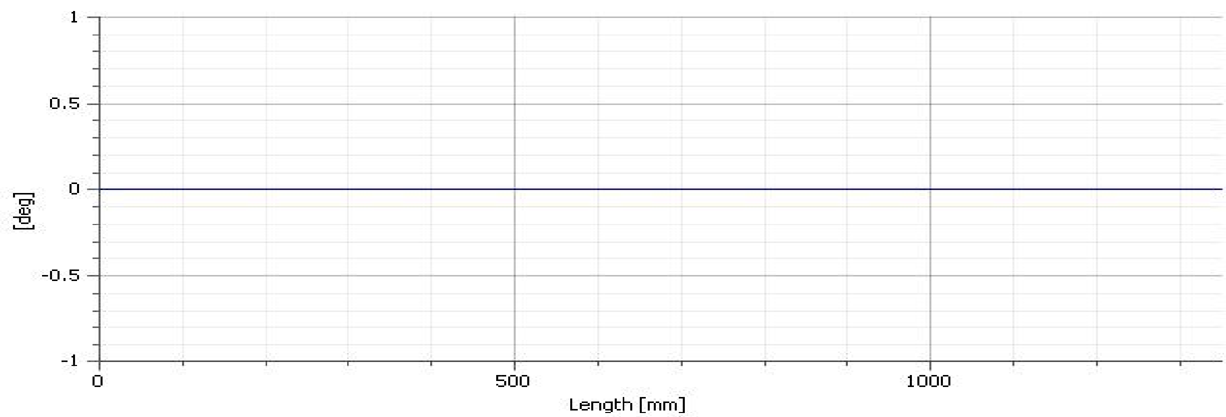

⊟ **Deflection Angle**



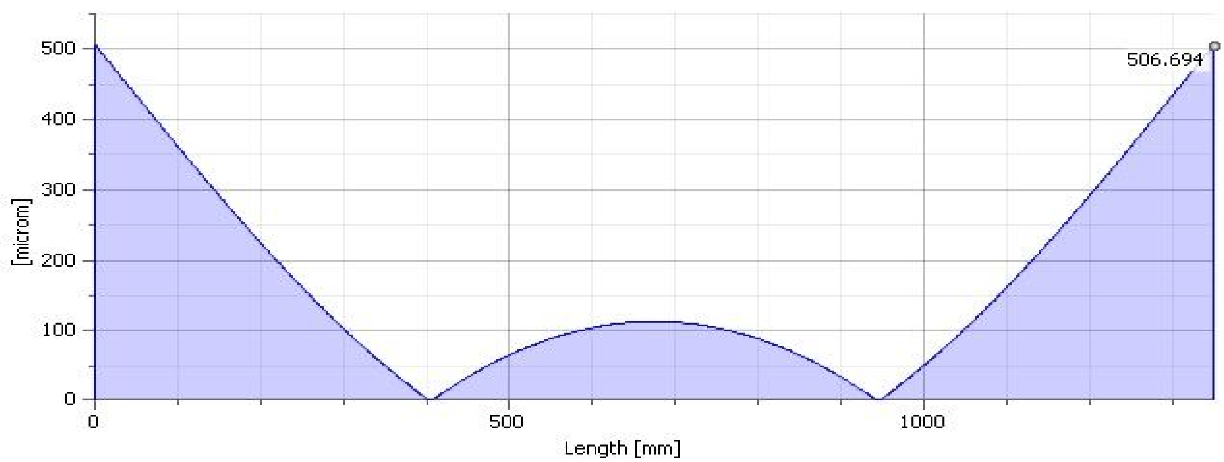

⊟ **Deflection Angle, YZ Plane**



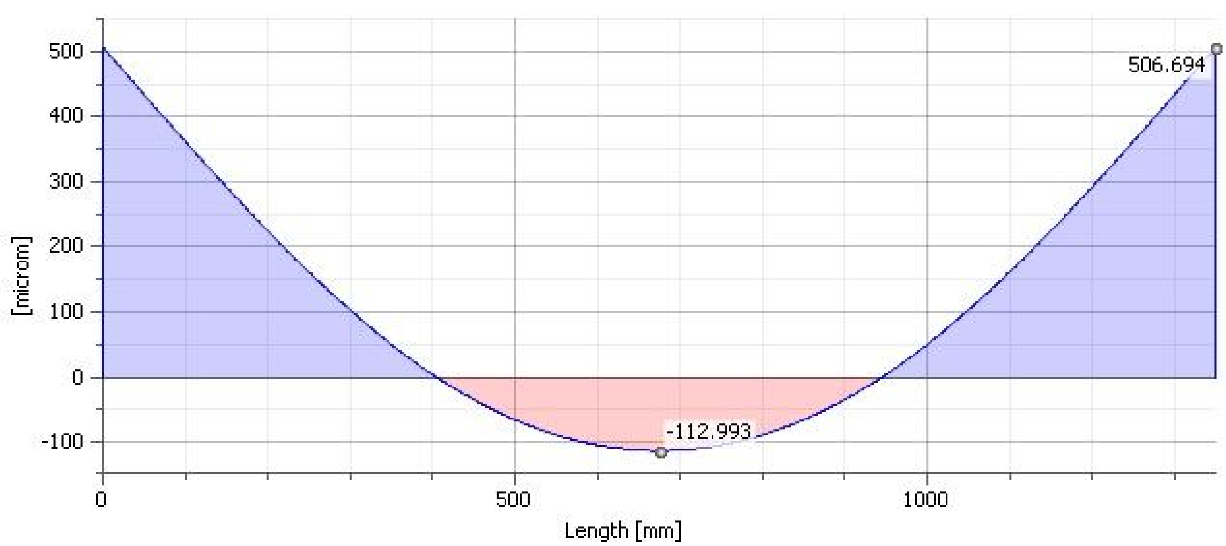
⊟ **Deflection Angle, XZ Plane**



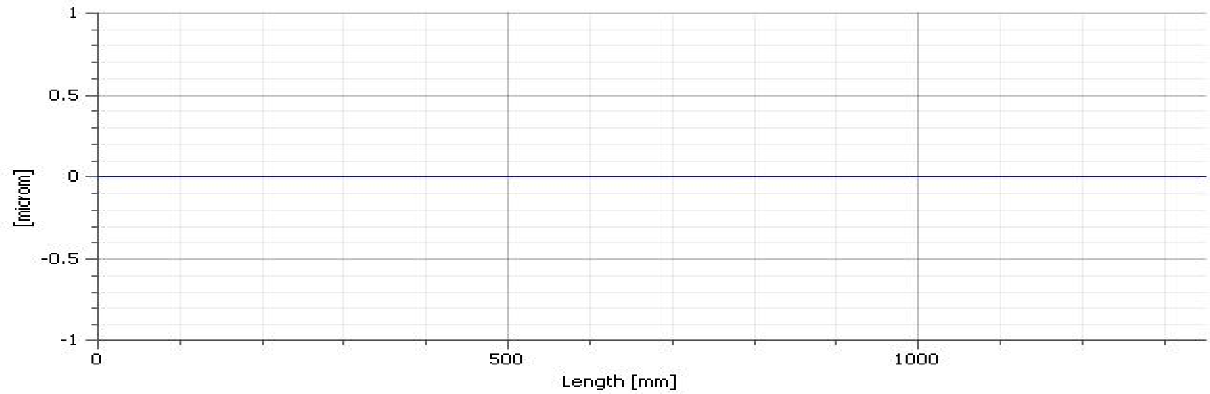

⊟ **Deflection**



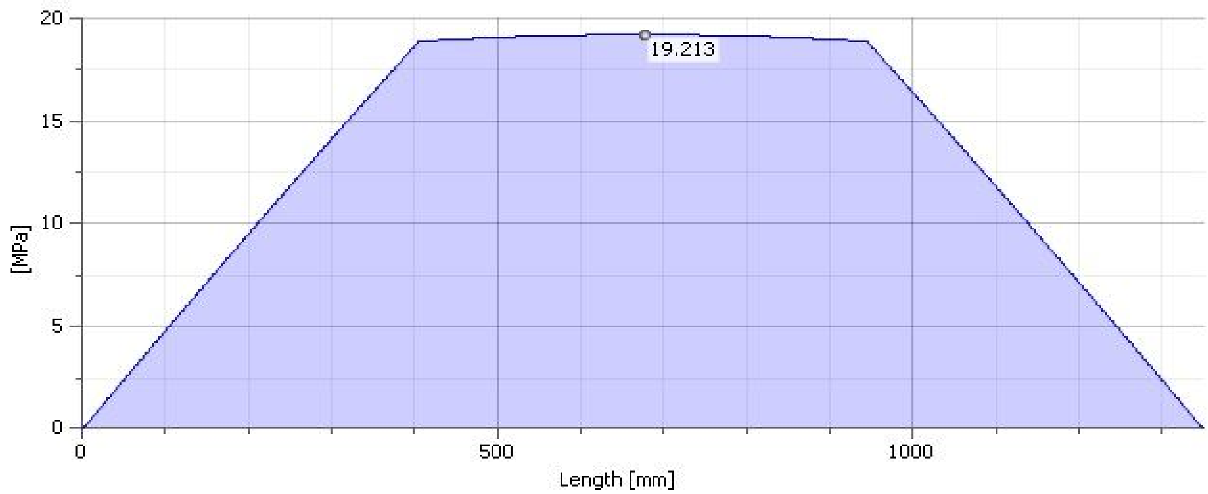

⊟ **Deflection, YZ Plane**



⊟ **Deflection, XZ Plane**

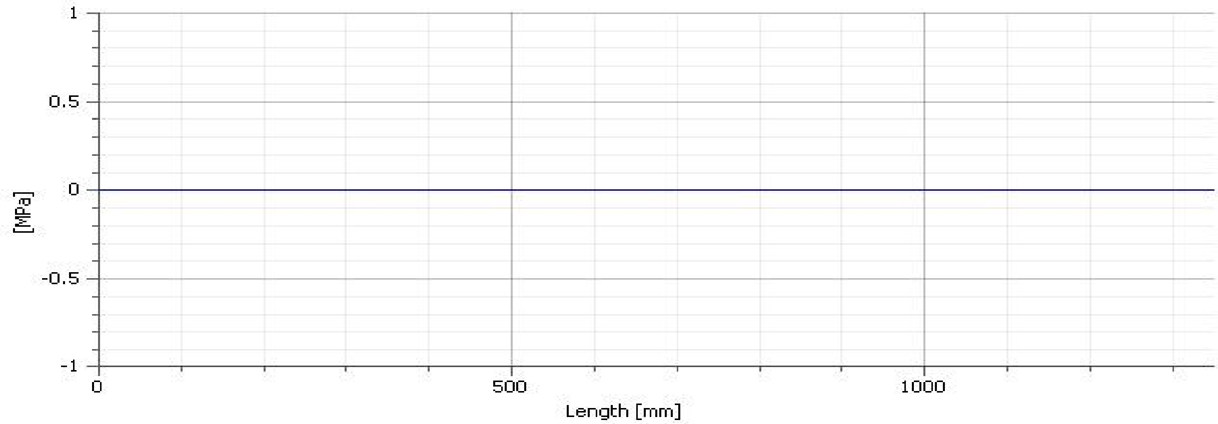



⊟ **Bending Stress**

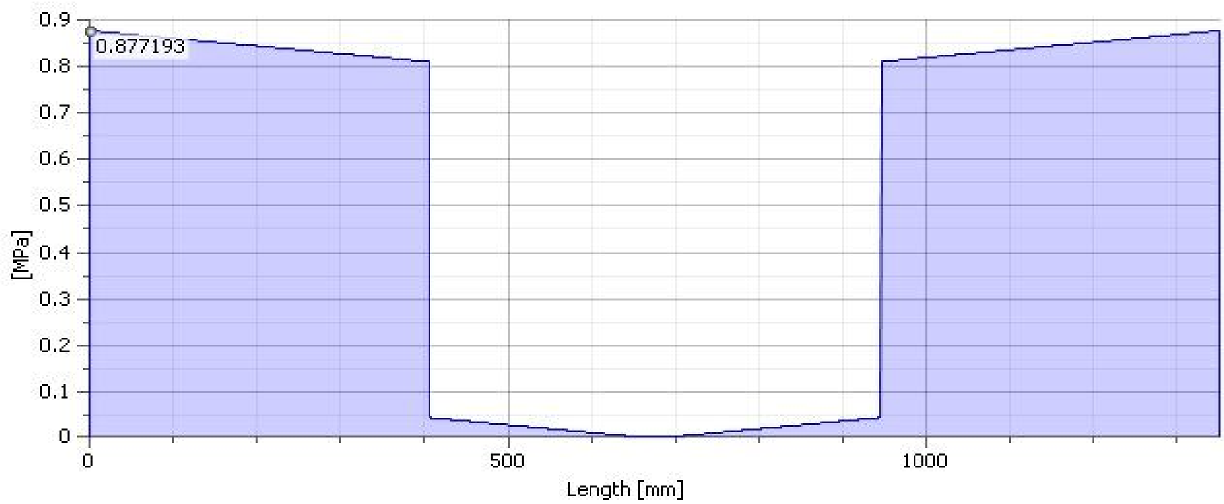



⊟ **Bending Stress, YZ Plane**

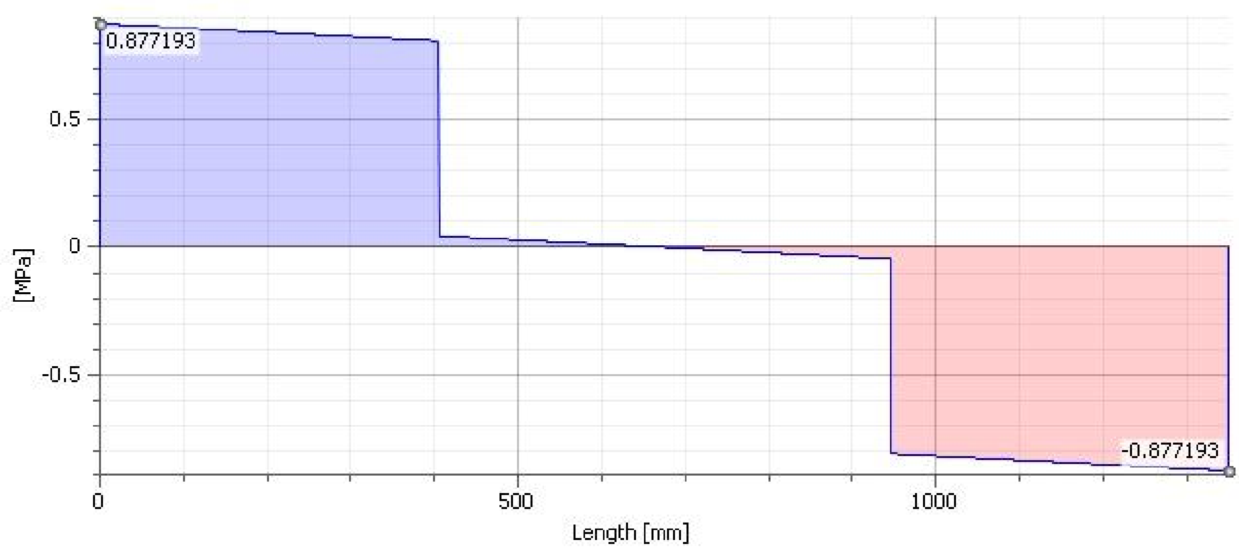
⊟ **Bending Stress, XZ Plane**



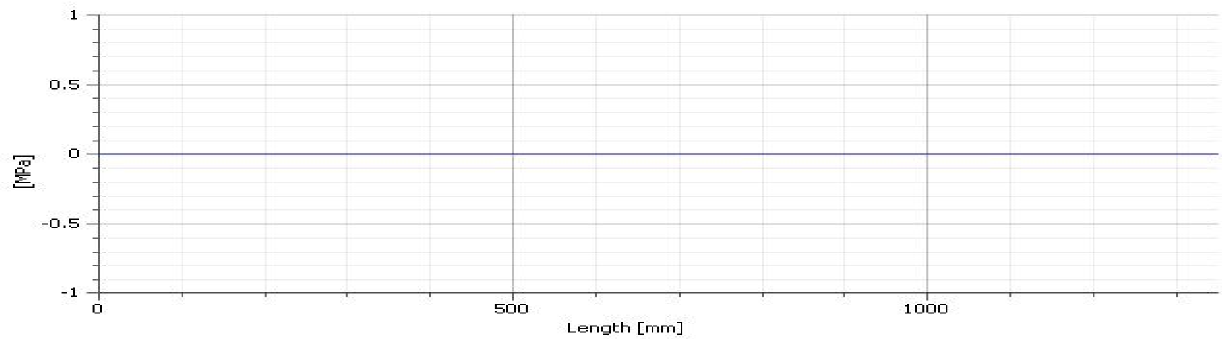

⊟ **Shear Stress**



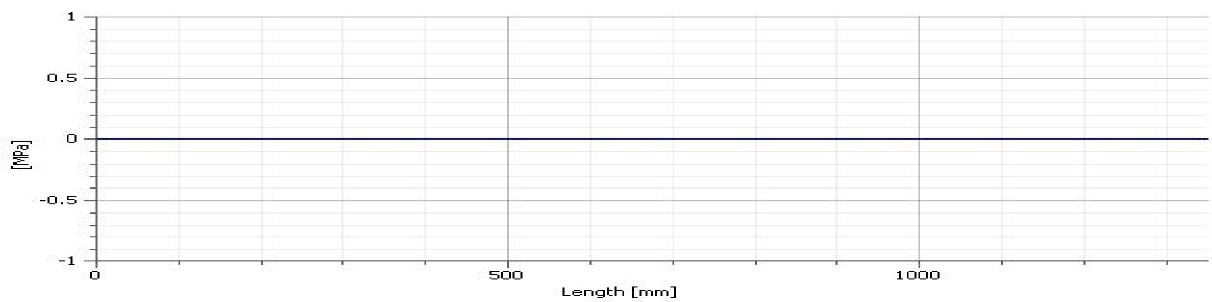

⊟ **Shear Stress, YZ Plane**



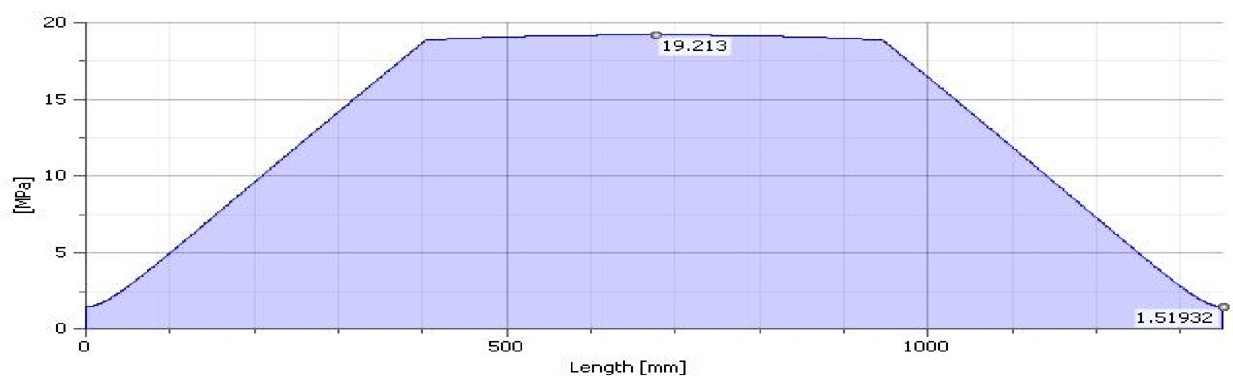
⊟ **Shear Stress, XZ Plane**




⊟ **Tension Stress**




⊟ **Reduced Stress**




⊟ **Ideal Diameter**

## *2. Upper Compression Bolted Connection:*

⊞ **Project Info**

⊟ **Static Calculation**

⊟ **Guide**

Type of Strength Calculation - Check Calculation

⊟ **Loads**

| | | |
|---|---|---|
| Tightness Factor | k | 1.50 ul |
| Maximum axial Force | $F_a$ | 1000 N |
| Force Input Factor | n | 0.50 ul |
| Maximum tangent Force | $F_t$ | 0 N |
| Joint Friction Factor | f | 0.40 ul |

⊟ **Bolt**

| | | |
|---|---|---|
| Bolt Number | z | 1 ul |
| Thread Diameter | d | 20.000 mm |
| Thread Pitch | p | 1.250 mm |
| Mean Bolt Diameter | $d_s$ | 19.188 mm |
| Minimum Bolt Diameter | $d_{min}$ | 18.466 mm |
| Material | | User material |
| Yield Strength | $S_y$ | 300 MPa |
| Required Safety Factor | $k_s$ | 3.00 ul |
| Allowable Thread Pressure | $P_a$ | 40 MPa |
| Modulus of Elasticity | E | 206700 MPa |
| Thread Friction Factor | $f_1$ | 0.20 ul |
| Head Friction Factor | $f_2$ | 0.25 ul |

⊟ **Material**

| | | |
|---|---|---|
| Joint Functional Width | L | 70.000 mm |
| Modulus of Elasticity | E | 206700 MPa |

⊟ **Results**

| | | |
|---|---|---|
| Prestress Force | $F_v$ | 1380.000 N |
| Working Force | $F_{max}$ | 1500.000 N |
| Required Tightening Moment | $M_u$ | 8.234 N m |
| Tensile Stress | $\sigma_t$ | 5.153 MPa |
| Torsional Stress | $\tau_k$ | 6.660 MPa |
| Reduced Stress | $\sigma_{red}$ | 6.660 MPa |
| Stress from Maximum Force | $\sigma_{max}$ | 5.601 MPa |
| Thread Pressure | $p_c$ | 2.853 MPa |
| Strength Check | | Positive |

## ***Remark:***

*No Need for the other parts calculations as they are used in the car conventionally and no stresses calculations are needed for them.*

## 4.7. Motor Mounting:

The motor mounting is done using 4 screw bolts and fix them in something rigidly attached to our system so we design **L** to satisfy our needs of fixation as shown is pictures below.

*Fig.4.38. Geared DC motor and its sprocket and chain*

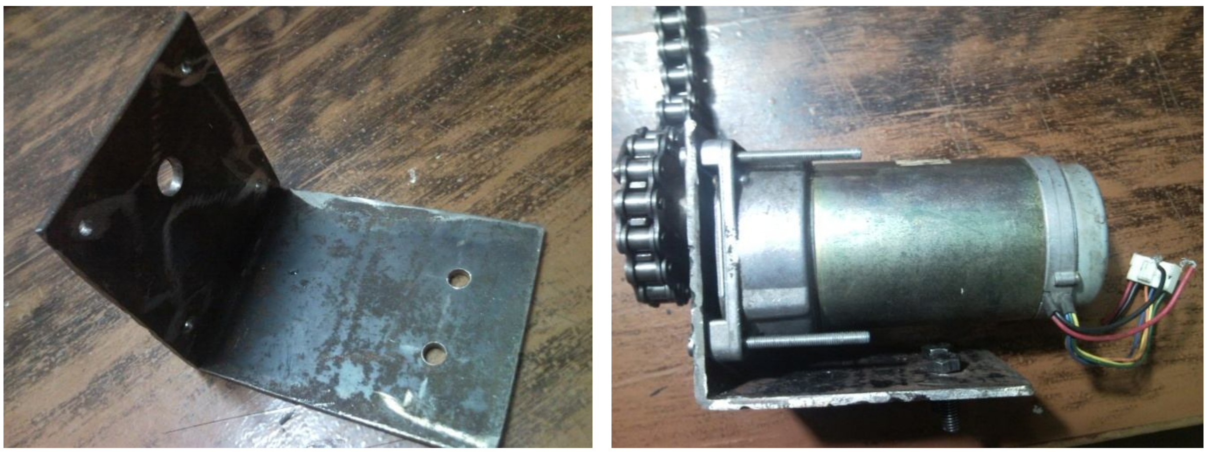


*Fig.4.39.* ***L*** *to hold motor and fix it to base plate*

*Fig.4.40. Motor mounting on base plate*

## ***4.8. Safety:***

During Machining, Cutting you have to take care from getting injured as you deal with dangerous tools, so your first aid tools is very important to be on work field.

During our work, many twist drills have been broken while fixed in the chuck and and it was so dangerous when it hurry to anyone around the machine. It could make dangerous injury.

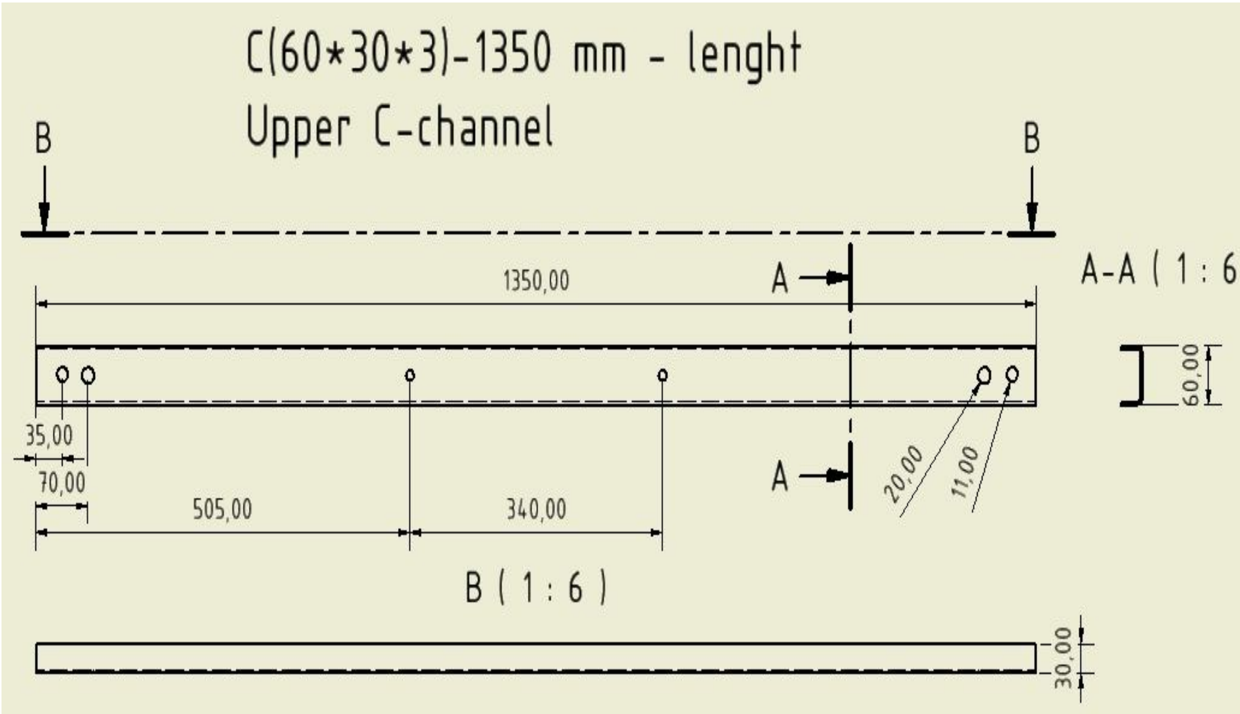
*Fig 4.41 An injury for one of team members*

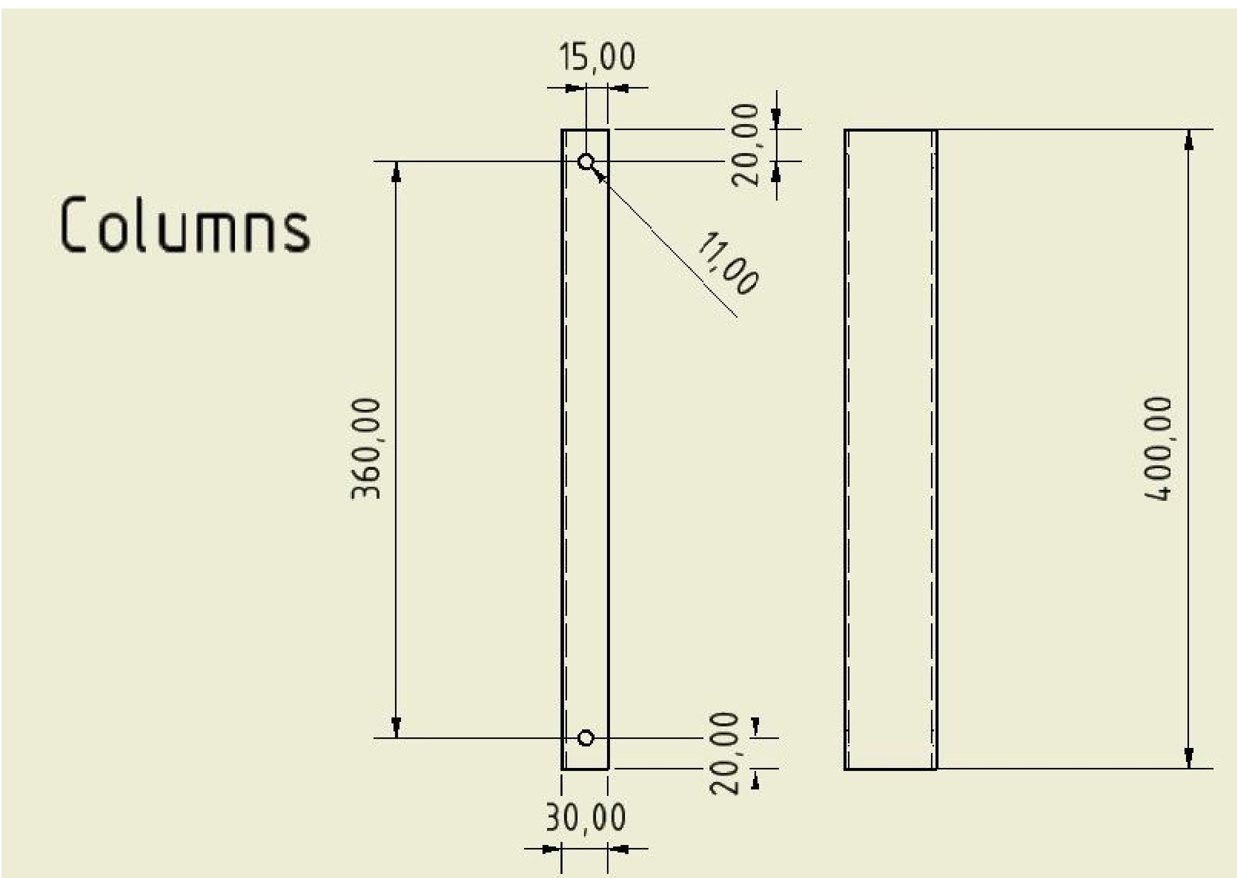
***Safety precautions related to a machine:***

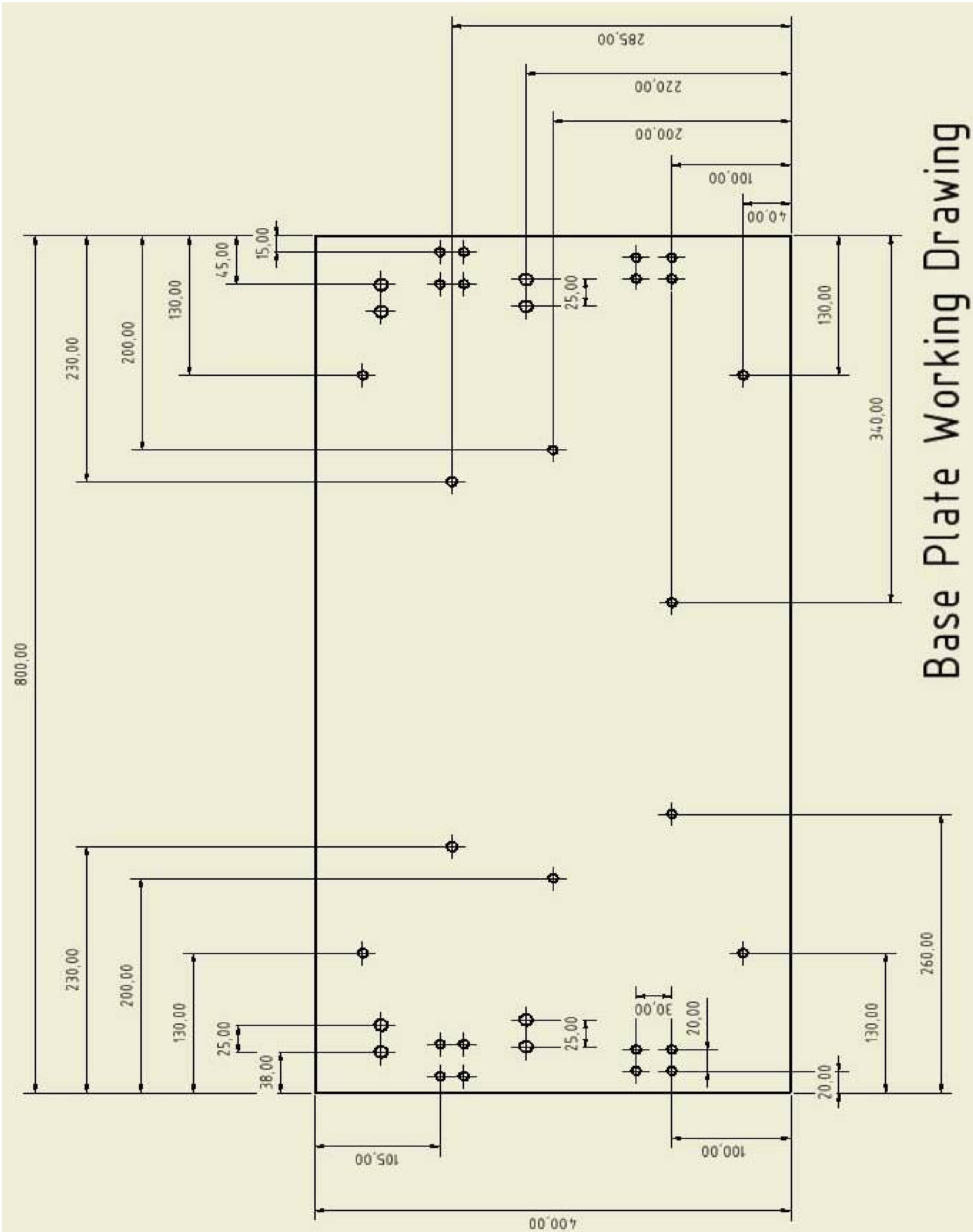
a) Never leave it unattended when the power source is switched on. Unplug from the power source when not in use.
b) Make sure the cord is plugged directly into the power source and is not sharing the source with another appliance.
c) Turn the machine off before moving it.
d) Do not touch the machine when your hands are wet or set the machine near water.
e) Make sure the machine is setting on a solid level surface.
f) Discontinue use if the electrical cord is wet, frayed or damaged in any way.
g) Step down from the plate only when it has completely stopped.
h) It is intended for indoor use only.
**i)** Inspect and tighten all parts on a regular basis.

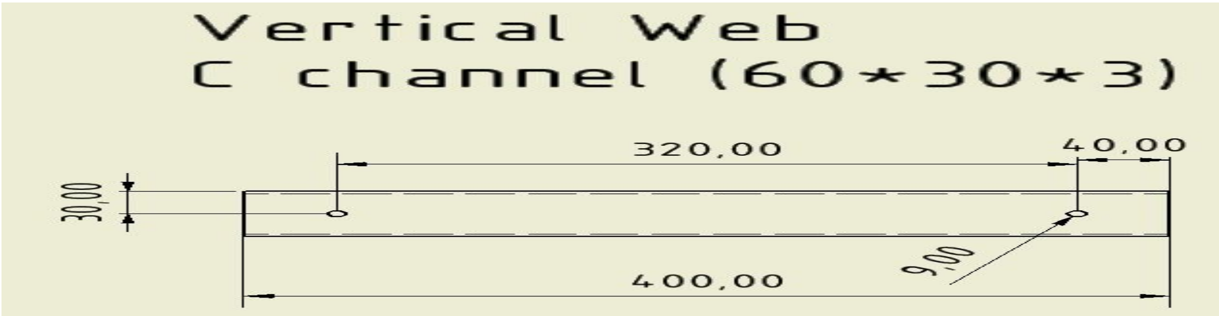
***Finally, the operator should wear all required safety glasses and ear protection.***

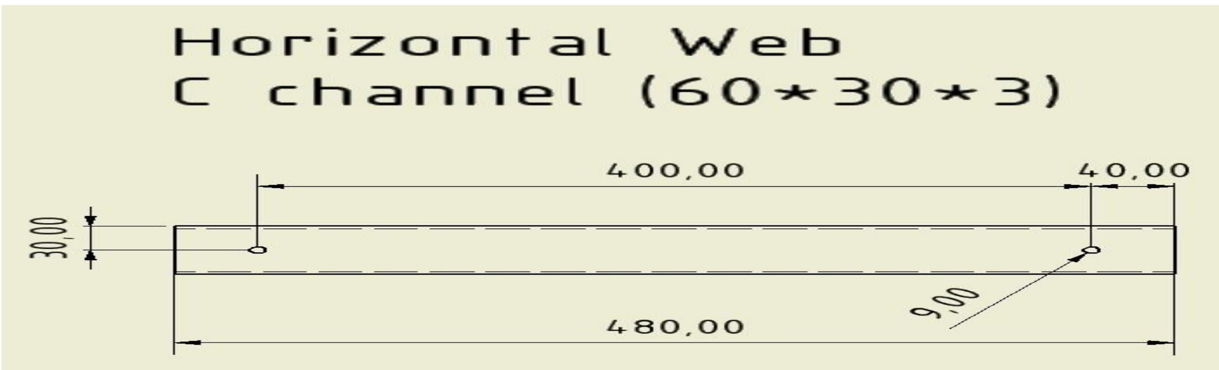
### *4.9. CAD drawings:*

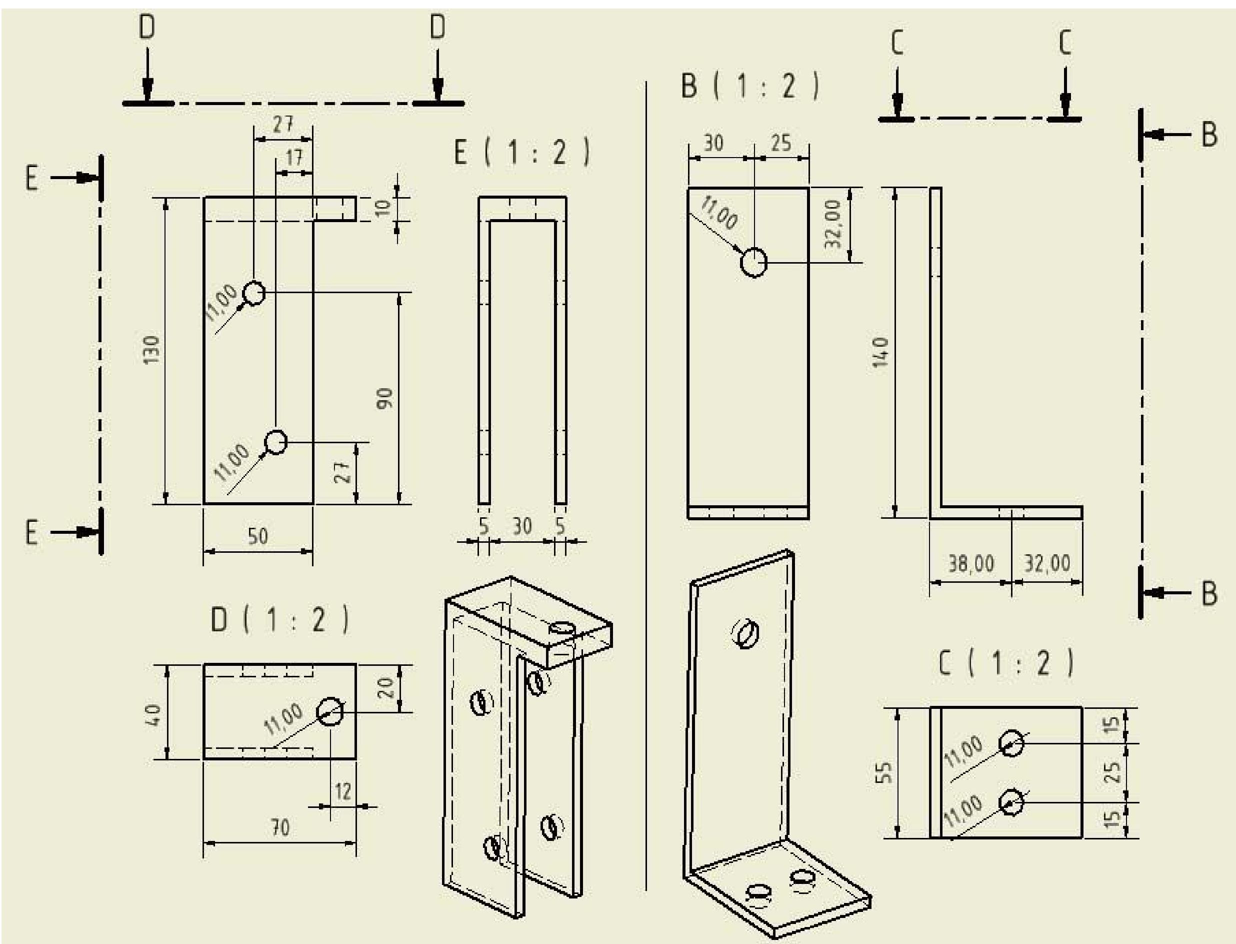



Base Plate Working Drawing
285,00
220,00
200,00
100,00
40,00
15,00
45,00
130,00
200,00
230,00
800,00
25,00
130,00
340,00
260,00
230,00
200,00
130,00
25,00
38,00
25,00
30,00
20,00
20,00
130,00
105,00
100,00
400,00

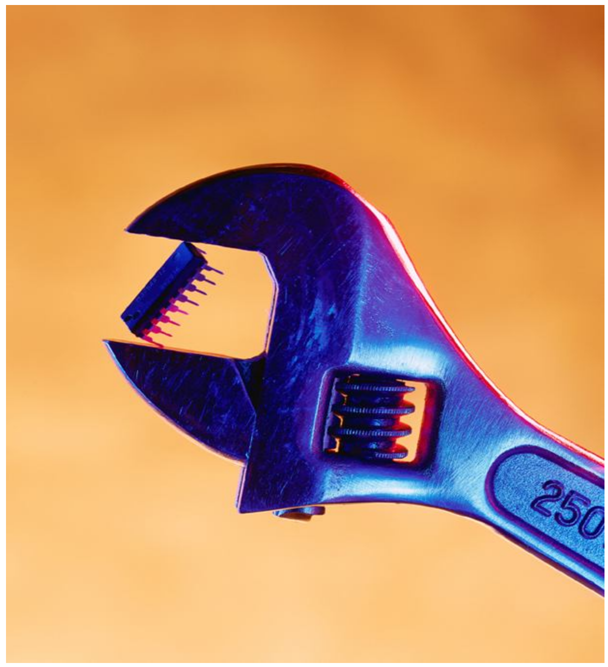

Vertical Web
C channel (60*30*3)
320,00
40,00
30,00
9,00
400,00


Horizontal Web
C channel (60*30*3)
400,00
40,00
30,00
9,00
480,00


D
D
E
E
27
17
10
130
11,00
11,00
90
27
50
E ( 1 : 2 )
5
30
5
D ( 1 : 2 )
40
20
11,00
12
70
B ( 1 : 2 )
30
25
11,00
32,00
C
C
140
38,00
32,00
B
B
C ( 1 : 2 )
55
11,00
11,00
15
25
15

# Chapter 5

## Control (PART ONE)



# CHAPTER 5

## 5.1. Motor Selection:

After the mechanical chassis design, it was necessary to select, and purchase a motor that is capable to actuate the pinion that is located in the steering system.

So the first step is to calculate how much torque needed to actuate the pinion.

### Determining the torque needed by the motor:

*As we know that*: $T = \mu \times F \times L$

***Where:***

- T: Torque generated at one of the front wheels.
- μ: Coefficient of friction between the tires and the road.
- F: Automobile own weight divided by 4(due to presence of 4 wheels).
- L: Geometrical distance.

### In Reality:

- Coefficient of friction between asphalt and tires: about **0.7** for dry roads and **0.4** for wet roads.
- Assume that the automobile having an own weight of 800 kg, so the normal force at each tire is 200 kg.
- This means that: $F = 200\ (kg) \times 9.8\ (m/s^2) = 1960$ N.
- This leads to: $T = 0.7 \times (200 \times 9.8) \times 0.1 = 137.2$ N.m.

### Our Steering System:

- Coefficient of friction between steel and tires: 0.6 to 0.7.
- Assume that the system having an own weight of 100 kg, so the normal force at each tire is 100 kg.
- This means that: $F = 25\ (kg) \times 9.8\ (m/s^2) = 245$ N.
- This leads to: $T = 0.6 \times (25 \times 9.8) \times 0.1 = 14.7$ N.m.

But the preceding calculated torque is going to be reduced through our gear box (rack and pinion of the steering system).

We have searched to find how to calculate the rack and pinion reduction ratio, but we couldn't find a clear way to do that.

So, we have assumed that the torque after the rack and pinion reduction is less than ***10N.m.***

***Conclusion:*** *A DC motor with the following specifications is needed:*

**Volt:** 24 volt

**Torque:** 10 N.m.

Afterwards we have visited Al-Gomohuria street to purchase this motor but we have found the following:

- ***DC Motors :***
    a. 24 Volt, 20 lb-in = 2.26 N.m, 46 rpm, with Gear box, price : 275
    b. 24 Volt, without Gearbox, Price : 75
- ***Servo DC Motor:*** 24 Volt Price 120

As it seems, there wasn't a full specifications for these motors, and they were seemed to be expensive than their real price.

So, after getting some support, we have reached AL-RAMLI shop in ROD EL-FARAG (beside AL-DONBSCO Institute).

This shop was full of DC-MOTORS, but unfortunately we have faced the same problem, that is the lack of the specifications.

So, we have decided to purchase any DC-MOTOR (starting with reasonable size), and then measuring it's stall torque and stall current, if they were not sufficient, we would replace it by another one, and so on until we reach the desired DC-MOTOR.

This is the photo of our first purchased Geared DC-MOTOR:

*Fig5.1. our first purchased motor*

It had some written specifications which are: DC 24 volt, 300 rpm.

We have surfed the internet to find its datasheet, but we didn't find it. All what we get was some specifications from an engineering forum.

***These specifications:***

*Engine TYPE:* DCG-5216-060
*Engine data:* 24 V DC motor 300rpm
*Gearbox* 10:1
*Weight with gear:* 1760 gr
*Motor Casing dimensions:* Diameter 70 mm Length: 113 mm
*Gearbox dimensions:* H.B.T 80 mm x 80 mm x 35 mm
*Wave.:* 10 mm
*Wavelength:* 40 mm

We tried to contact the manufacturing company which located in JAPAN, but they refused to provide any further support of this motor's specifications for security purposes.

So, the main objective was to measure the stall current and the stall torque.

### *5.2. How to measure the stall torque of the motor s well as the stall current:*

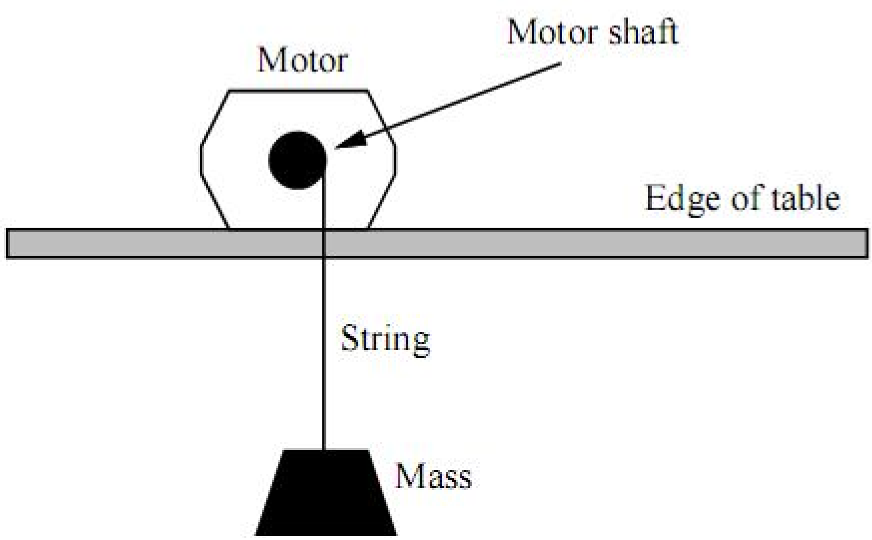



*Fig 5.2.Measuring the stall current Experiment arrangement*

Motor torque (momentum) is one of motor ratings which is used to indicate motor rotary force produced on its output shaft. Motor torque rating is usually captured at point when motor is stalled. Torque measurement unit is (Nm) in metric system or (ft lbs) in US system. But principle is the same torque is a multiplication of lever length (r) and force(F) applied to lever.

Torque = r × F

All you need is a motor of which torque will be measured, nominal power supply of motor, thread long enough, a mass of known weight, ruler and a table or other lifted surface where motor will be fixed.

Attach mass to one end of string and other end tie to motor shaft so that it could turn the windings. Fix the motor at the edge of table so that string with mass would hang. Start the motor and led the rotating shaft to wind the thread while lifting the mass. At the beginning motor will turn very easily but later when radius of winding will increase so the stopping force will increase also. And at last motor will stall. So this is the moment when you have to stop the motor and measure the radius of winding.

$T = r \times m \times g$

If motor will windup all thread try to attach heavier mass. This technique will help to compare different motors or test motors torque and compare to documentation to see how reliable is this technique.

*But we have made some modifications on the previous way.*

## 5.3. Actual Methods that have been used to measure the stall torque and stall current of the motor:

*First Method*

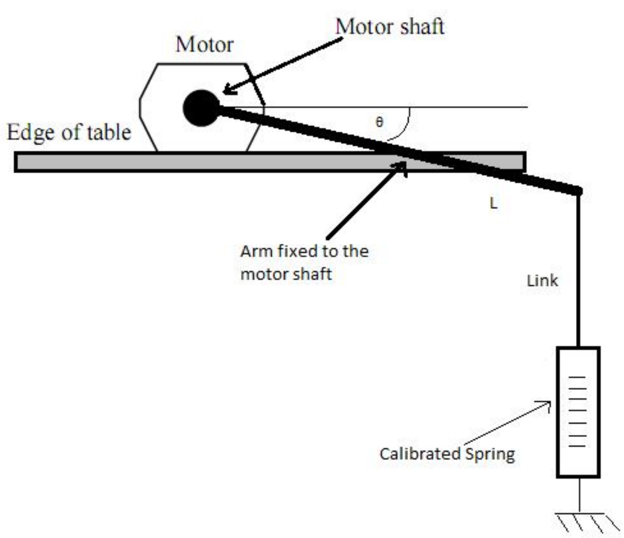



*Fig 5.3.First Method Configuration*

## Steps:

1. *Fix an arm to the motor shaft*

*Fig 5.4.Fixing an arm to the motor shaft*

*2. Fasten the motor on the vice.*

*Fig 5.5.Motor mounting on the vice*

*3. Attach a calibrated spring to the end of this arm*


*Fig 5.6.Calibrated Spring Attachment*

*4. Attach the other end of the calibrated spring to a huge weight.*

*Fig 5.7.Attaching a weight to the calibrated spring*

*5. Connect an AVOMETER in series with the motor (in order to measure the stall current).*
*6. Apply the voltage (24 volt) to the motor (typically maybe a two car batteries, each one is 12 volt, connecting them in series gave us 24 volt).*
*7. The arm will begin to rotate, when stops the motor is stalled.*
*8. Examine the calibrated spring reading.*

*Fig 5.8.examine the calibrated spring reading*

*9. Write down the AVOMETER reading (stall current).*
*10. Record the angle that the arm makes with the horizontal plane.*
*11. Collapse the voltage source that is connected to the motor.*
*12. Compute the stall torque from the relation:*

T (N.m) = m(kg) * g(m/s2) * L(m) * cos θ ,where:

- T: Stall Torque
- m: Calibrated spring reading
- g: Gravity
- L: Arm Length
- Θ: the angle that the arm makes with the horizontal plane.

***So, we achieved the following results:***

*Stall torque* = 3(kg) * 9.8(m/s2) * 0.37 * cos20 = *10.22 N.m*

*Stall current:* At *12 volt:* stall current = *9.5 Ampere.*

At *24 volt:* stall current = *13.8 Ampere.*

***Very Important Remark:***

Do not stall the motor more than one or two seconds to prevent it from getting damaged.

### *5.4. Second Method:*

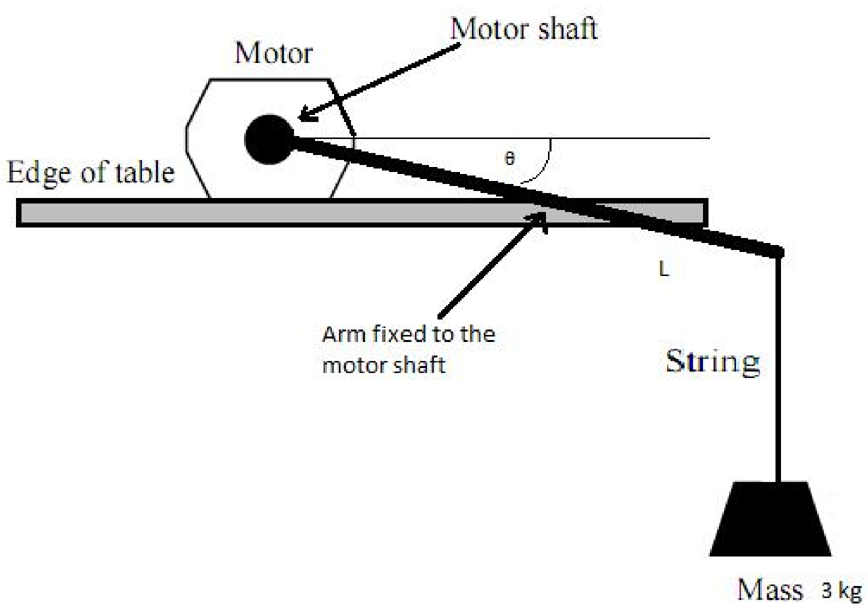



*Fig 5.9.Seconed Method Configuration*

The second method as shown resembles the first one in many ways, except in using variable masses instead of calibrated spring, i.e we have used a 3 kg mass ( After we have tested other masses, we realized that a 3 kg mass is capable of stalling the motor in less than one fourth complete revolution) to stall the motor and measure the inclined angle θ, as well as record the AVOMETER reading .

**And we have obtained nearly the same results:**

*Stall torque*: 3(kg) * 9.8(m/s2) * 0.37 * cos15 = *10.5 N.m*

*Stall current:* *At 12 volt* : stall current = *9.5 A*

*At 24 volt* : stall current = *13.8 A*

From this experiment, we could conclude that the motor specifications are:

- ***Stall torque:*** *10 N.m*
- ***Stall current:*** *13.8 Ampere (at 24 volt)*

  *9.6 Ampere (at 12v)*

The next step was to use an H-Bridge to control the motor's direction, but the large current that would flow through the motor prevents us from buying an H-Bridge as an integrated circuit, and we had to design one that could resist 15 Ampere.

## 5.5. H-Bridge:

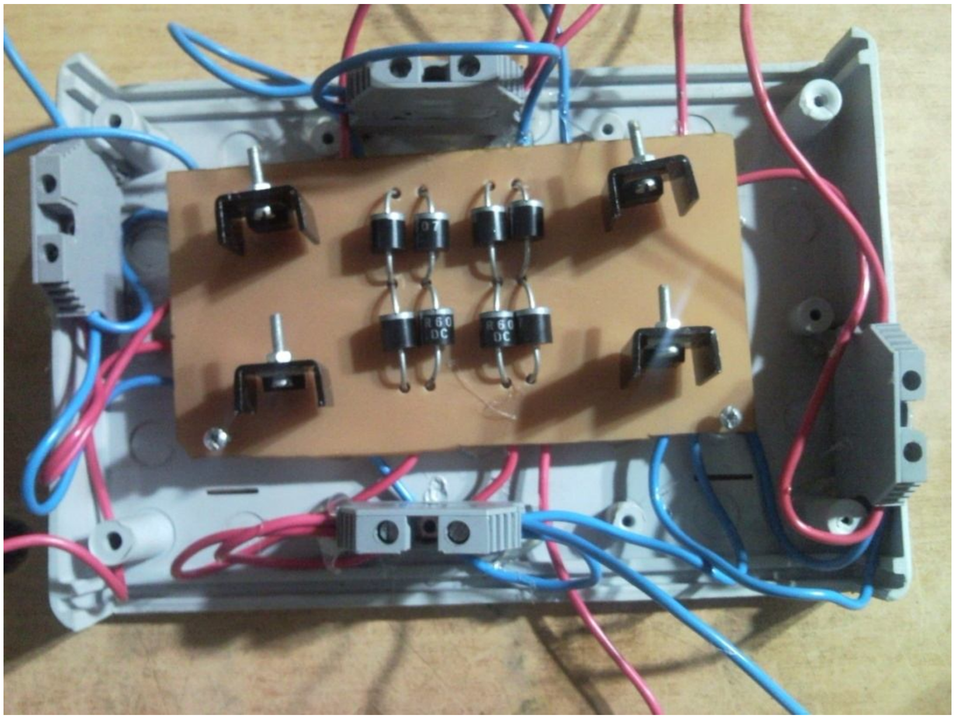


*Fig 5.10.H-Bridge*

### 5.5.1.Brief Description:

An H-bridge is an electronic circuit which enables a voltage to be applied across a load in either direction. In general an H-bridge is a rather simple circuit, containing four switching element, with the load at the center, in an H-like configuration:

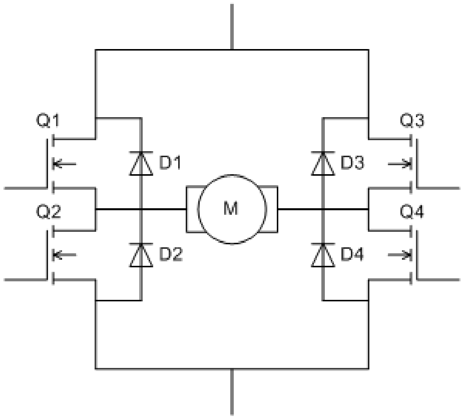



*Fig 5.11.basic H-Bridge using MOSFETs*

The switching elements (Q1..Q4) are usually bi-polar or FET transistors( PNP BJTs or P-channel MOSFETs connected to the high voltage bus and NPN BJTs or N-channel MOSFETs connected to the low voltage bus). The diodes (D1..D4) are called catch diodes and are usually of a Schottky type. Though they are mentioned in most documents dealing with H-bridges, their role is usually neglected.

### *5.5.2. Why we are going to make H-bridge?*

It's a commonly known fact to robotics why motor drivers are needed. 99.99% of the time, the micro- controller or control circuitry of a robot just can't provide the current needed to power motors. For motors with small current draw, single chip solutions such as the L293 or L298 can be used, however these are only useful for a range of less than one or two amps, but in our case more than 15 amps is not suitable for these types.

Our steer by wire system use a dc motor to control the motion of the wheels of the car so the motor will have two directions right and left so we should make our motor turn right and left when we apply a signal on it and by searching we found that the function of the H-Bridge is reversing the direction of the motor right and left using some switches and this is what we need.

So we decided to make an H-bridge .

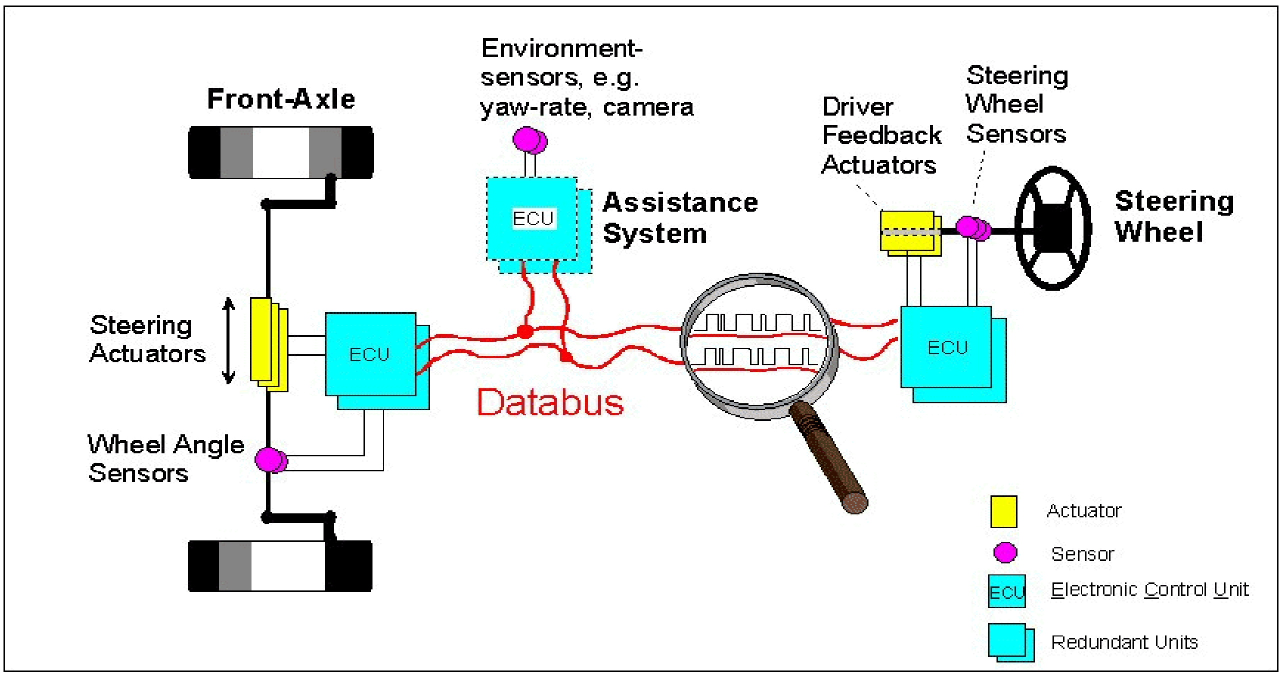



*Fig 5.12 Steer By wire System Configuration*

As shown in Fig 5. We may encounter an H-Bridge module in the left side of the photo inside the leftmost ECU.

### *5.5.3. Basic operation:*

The H-Bridge arrangement is generally used to reverse the polarity of the motor, but can also be used to 'brake' the motor, where the motor comes to a sudden stop, as the motor's terminals are shorted, or to let the motor 'free run' to a stop, as the motor is effectively disconnected from the circuit.

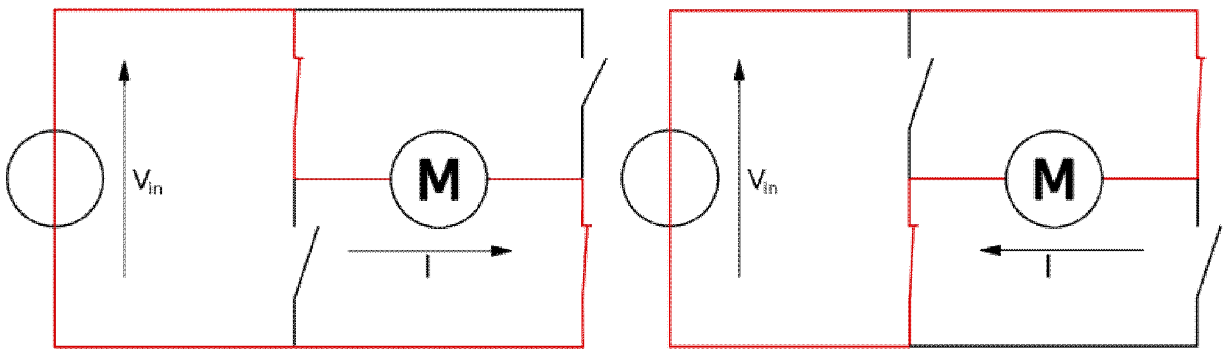
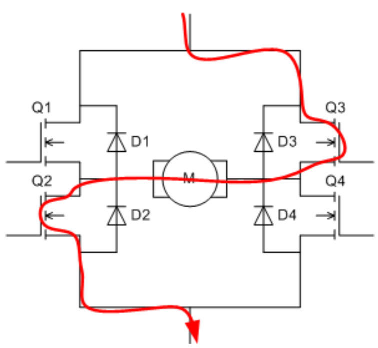


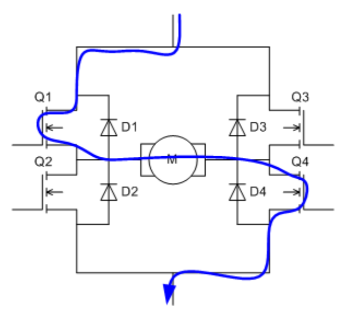

*Fig 5.13 Basic Operation of H-Bridge*

The basic operating mode of an H-bridge is fairly simple: if Q2 and Q3 are turned on, the left lead of the motor will be connected to ground, while the right lead is connected to the power supply. Current starts flowing through the motor which energizes the motor in (let's say) the forward direction and the motor shaft starts spinning. If Q1 and Q4 are turned on, the converse will happen, the motor gets energized in the reverse direction, and the shaft will start spinning in that way. If less than full-speed (or torque) operation is intended one of the switches are controlled in a PWM fashion. The average voltage seen by the motor will be determined by the ratio between the 'on' and 'off' time of the PWM signal.




**Current flow in the forward direction**

*Fig 5.14. Forward Direction*




**Current flow in the backward direction**

*Fig 5.15. Backward Direction*

### *5.5.4. Component selection:*

For the most part, the key decision to make for an H-bridge is the selection of the switching elements. There are many factors to be considered, the most important ones are the operating current, the operating voltage and the switching (PWM) frequency. For most cases a MOSFET switching element is a good selection.

- This H-bridge uses MOSFETs for one main reason - to improve the efficiency of the bridge. When BJT transistors (normal transistors) were used, they had a saturation voltage of approximately 1V across the collector emitter junction when turned on. The transistors also would get quite hot - no room for heat sinks.
- We chose MOSFETs because when they turn on they have an ON resistance called RDS (on). This is the resistance between the Drain and Source when turned on. It is quite easy to buy MOSFETs that have very low RDS (on) ratings of less than 0.1 ohm.
- Now, when a MOSFET has a low RDS(on) rating, it usually has quite a high current rating typically in the 10s of amps and that is what we need as our motor need more torque to move the system right and left and the more torque we need the more current we require .
- MOSFETS are very fast switches and have no mechanical error (they are solid state switches)
- So it is very good for our system as we need high speed and high accuracy in turning the wheels of our system.

It is easy to make the mosfets cool by using heat sinks and we make a good cooling system for it as it will show.

*Why we didn't use relays in our H-bridge:*

As it is a mechanical device and have low response and low life time so it will not be efficient for our system which needs very high response.

So, we will use ***MOSFETS*** in our design.

MOSFETs work by applying a voltage to the Gate. The input Gate voltage controls the output Drain current. They call this transconductance. When a positive voltage greater than the Gate threshold voltage is applied, the MOSFET turns on.

MOSFETs are extremely static sensitive but more important is that if the Gate is left open (no connection), the MOSFET can self- destruct.

MOSFETs, when operated as switches, have two states: on and off. In the 'on' state they have more or less behave like a small resistor. Their resistance is called channel resistance, and is denoted by $r_{dson}$. Obviously the higher this value is, the higher the losses are on the MOSFET.

While efficiency is not a big concern for most H-bridge designs, heat is. Since the loss on the MOSFET is converted to heat that has to be dissipated, the lower $r_{dson}$ is the better. Another factor to consider is that $r_{dson}$ is temperature-dependent and increases with temperature. Datasheets usually brag about $r_{dson}$ at $25^{o}C$, but that hardly can be considered as normal operating condition. So always look for $r_{dson}$ over the full temperature range to make sure you're operating within safe limits.

The heat dissipation is the most important thing that should be considered when making the H-bridge as it affects the current flowing in the circuit more heat will decrease the current and that is not good for high current devices like our motor and also it mean low life time for our H-Bridge.

Power MOSFETs are at risk of thermal runaway. As their on-state resistance rises with temperature, if the load is approximately a constant-current load then the power loss rises correspondingly, generating further heat. When the heat sink is not able to keep the temperature low enough, the junction temperature may rise quickly and uncontrollably, resulting in destruction of the device.

In our Circuit we have high current requirements for the motor and that make a lot of heat and we are very concerned with the heat as it may cause our circuit to be destruct and for the steer by wire system it means fail of the system if any bad things like that occurred in our H-Bridge and that means accidents.

A related decision to make is to decide if 'N'-channel or 'P'-channel MOSFETs are used. 'N' channel MOSFETs have a much lower $r_{dson}$ values but they are hard to control on the high-side (Q1 and Q3). In general the low-side switches are always 'N'-channel transistors, while the high-side ones are sometime 'N' and sometime 'P' type.

So in our system we used P channel mosfets for the high side switches and n channel mosfets for the low side switches. You should take care of this alignment or you will have bad responses from the circuit.

In our Circuit the minimum current is 10 amps and that is not a small current value and it cause a lot of problems for us and one of this problems is the more heat generated on the MOSFETS.

### 5.5.5.Catch diodes:

Catch diodes (D1..D4) are often overlooked or just briefly mentioned in most H-bridge descriptions, but they are very important components.

The basic principle is very simple: while the bridge is on, two of the four switching elements will carry the current,

the diodes have no role. However once the bridge is turned

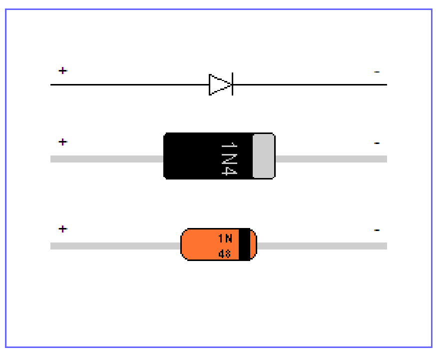


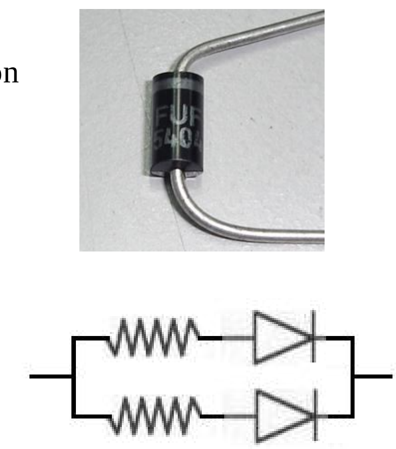

*Fig 5.16 Catch Diodes*

off the switches will not conduct current any more. As discussed earlier, by far the most common load for an H-bridge is an electric DC motor, which is an inductive load. What this means is that during the on-time the motor will build an electromagnetic field inside it. When the switch is turned off, that field has to collapse, and until that happens, current must still flow through the windings. That current cannot flow through the switches since they are off, but it **will** find a way. The catch diodes are in the design to provide a low-resistance path for that collapse current and thus keep the voltage on the motor terminals within a reasonable range.

For our circuit we should use high current diodes up to 10 amps as the current is high which pass in the motor and if we put small diodes it will destruct in the starting time causing the mosfets to fail shortly.

***<u>Why we use fast recovery diodes?</u>***

Our system need fast switching to make the motor come to the right position very fast without making oscillation around the actual position as we use a very accurate encoder and that make us reversing the direction of the motor very fast and that will not be good if we use a standard diodes  so we buy fast recovery diodes.



So we searched for high current fast recovery diodes and we found the maximum fast recovery diode is 6 amps and we need higher than this value so we put to diode in parallel which make the current became up to 10 amps ,and this is a reasonable value .

*Fig 5.17.Fast Recovery Diodes*

Actually the design of the H-Bridge wasn’t our work it was the work of another group working with our supervisor and we take the concept from them and then we begin to modify the circuit to obtain our needs .

## *5.6. Given Design Layout:*

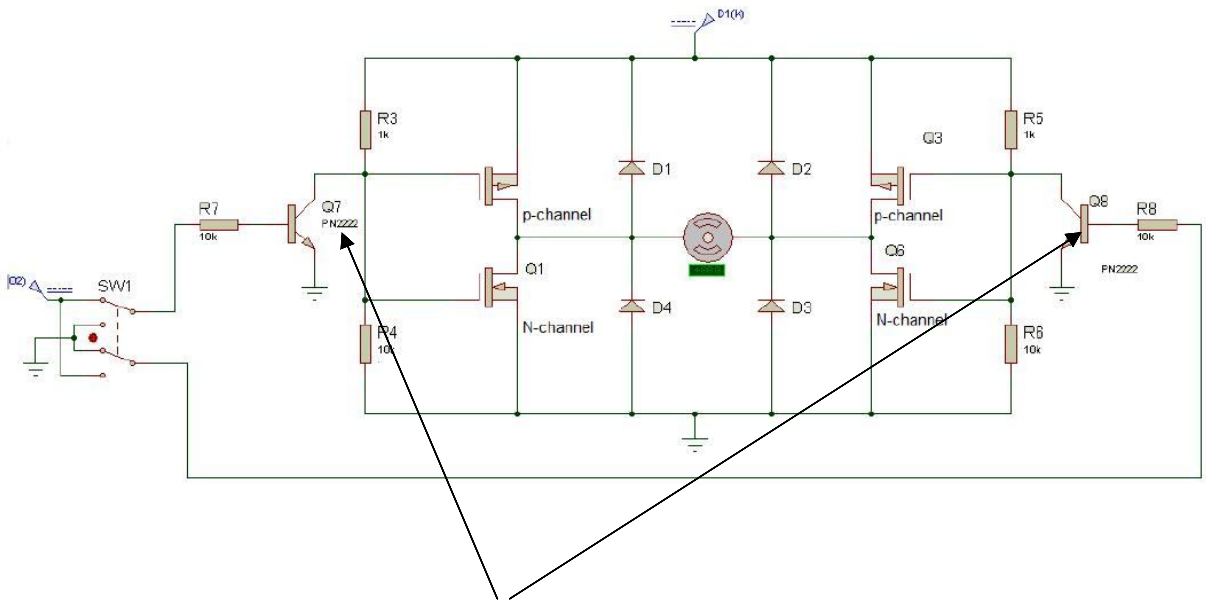



*Fig 5.18.Given Schematic H-Bridge*

As shown in the figure there are two transistors to activate the gates of the MOSFETs ,We used NPN transistor which is active by zero signal so to deactivate we use one signal and this signals is coming from the microcontroller which control the whole system and it gives the order to the motor to turn right or turn left with very high speed switching as we want, and we tested it a lot of times and it make the best benefits from using it.

By studying this circuit, we found that the two MOSFETS types **N-channel IRF 540, 100V, 00.50 ohm, 30A** and **P-channel IRF 9540N, -100V, 0.117 ohm, 23A,** that have been used <u>*would be safe*</u> for our motor current which is nearly 14 Ampere as a stall current.

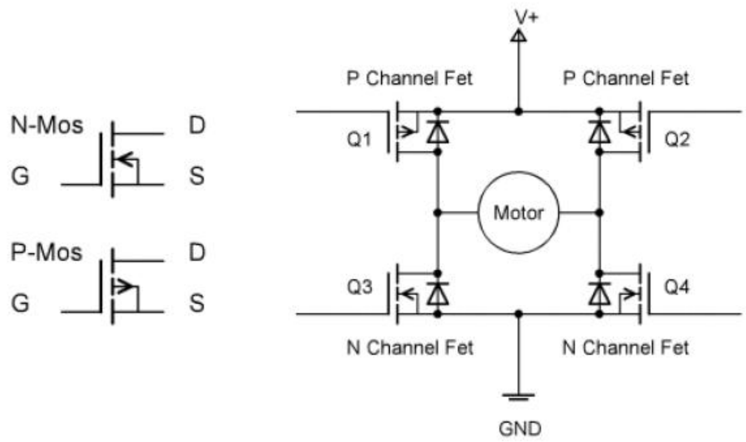



*Fig 5.19.P and N MOSFETs*

## *Important Remarks:*

For the MOSFETS we use as shown in the table below it has a temperature range from -55 to +175

And it is a high temperature which the circuit cannot resist so it needs good cooling conditions to make the circuit do its best efforts in our system.

| | Parameter | Max. | Units |
|---|---|---|---|
| $I_D$ @ $T_C$ = 25°C | Continuous Drain Current, $V_{GS}$ @ -10V | -23 | A |
| $I_D$ @ $T_C$ = 100°C | Continuous Drain Current, $V_{GS}$ @ -10V | -16 | |
| $I_{DM}$ | Pulsed Drain Current ① | -76 | |
| $P_D$ @$T_C$ = 25°C | Power Dissipation | 140 | W |
| | Linear Derating Factor | 0.91 | W/°C |
| $V_{GS}$ | Gate-to-Source Voltage | ± 20 | V |
| $E_{AS}$ | Single Pulse Avalanche Energy② | 430 | mJ |
| $I_{AR}$ | Avalanche Current① | -11 | A |
| $E_{AR}$ | Repetitive Avalanche Energy① | 14 | mJ |
| dv/dt | Peak Diode Recovery dv/dt ③ | -5.0 | V/ns |
| $T_J$<br>$T_{STG}$ | Operating Junction and<br>Storage Temperature Range | -55 to + 175 | °C |
| | Soldering Temperature, for 10 seconds | 300 (1.6mm from case ) | |
| | Mounting torque, 6-32 or M3 srew | 10 lbf•in (1.1N•m) | |

*Fig 5.20.Table shows the temperature range for MOSFETS*

We used good heat sinks for our mosfets and we also used small PC fans to speed up the heat dissipation operation.


*Fig 5.21.FAN used*

We have divided the given circuit design into two circuits, a controlling one (Module 1) that do not see a large current, and a controlled one that bypass the large motor current.

We think about that to isolate the high power circuit with its complicated problems from the control circuit which have small current values.

And that helped us and will help in the coming researches which will work on our project to make it easy to change the control module as easy as they desire and to use the High Power Module of the H-bridge (which have a lot of problems that have been solved). And this will simplify their work.

## The following consequences describe the full work of the H-Bridge:

1. Circuit components list
2. Module 1 layout
3. Module 1 PCB layout
4. Module 1 Real PCB Circuit
5. Module 2 layout
6. Module 2 Real Circuit
7. Complete circuit configuration

## 5.7. Building the H-Bridge:

### 1) Circuit components list

- MOSFET IRF9540. # 2
- MOSFET IRF540. #2
- Transistor 2222A. #2
- Fast diode #8
- Resistance 10k. #6
- Resistance 1k. #2
- Heat sink. #4
- Electrical Rosetta.

### 2) Control circuit layout :

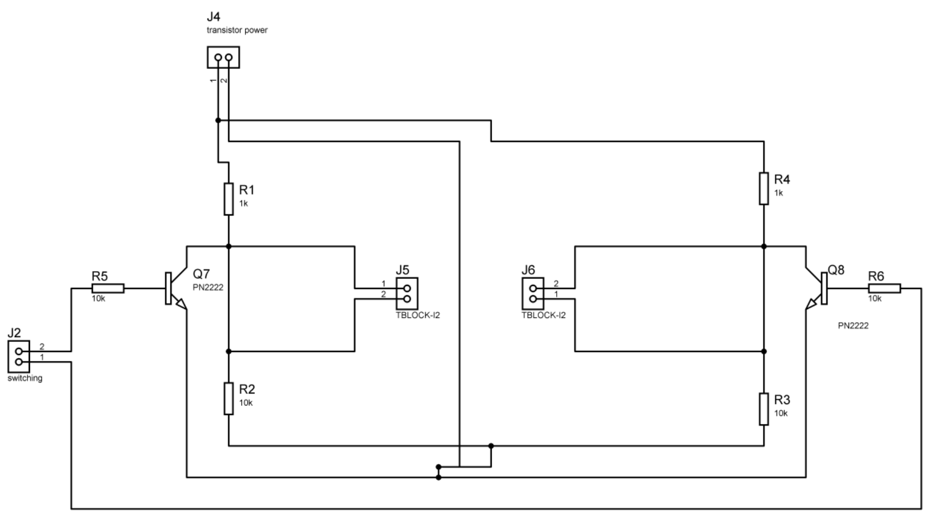



*Fig 5.22.Control Circuit Schematic*

As shown in the above figure (the control module) we find transistors and resistances and some terminal blocks which connect the module with other circuits:

- Terminal Block J2 to receive signals from the microcontrollers
- Terminal Blocks J5&J6 to connect the module with the high power circuit as these connections will be connected to the gates of the mosfets.
- Terminal Block J4 is used as a power to open the mosfets gates.

3) *Then we make the PCB layout for our control circuit:*

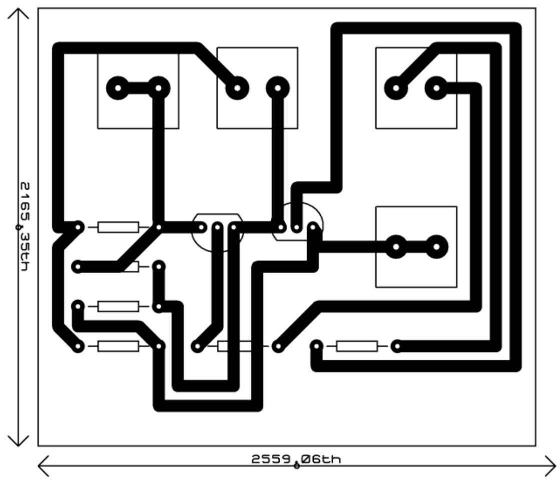



*Fig 5.23.Module 1 PCB layout*

4) *After that we print it out and we made the PCB for it and here is the circuit:*

*Fig 5.24.Module 1 Real PCB*

5) High Power Module layout (Module 2):

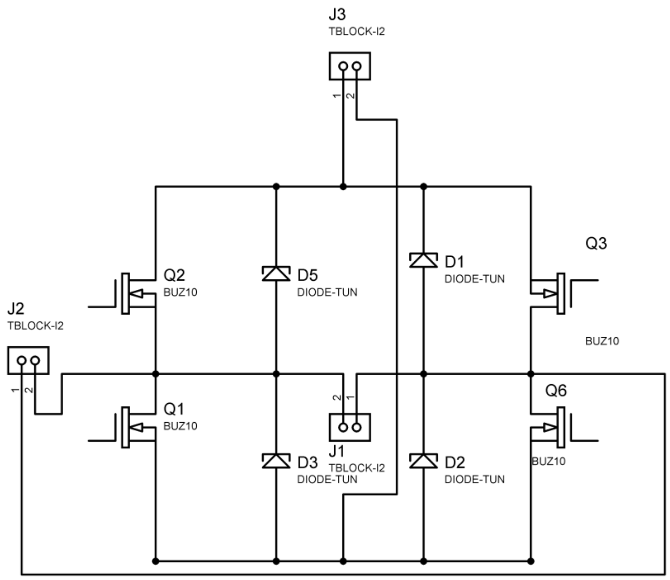



*Fig 5.25.Module 2 Schematic*

The most complicated part in our H-Bridge is this circuit and the main reason for these problems is the high current which is applied to the motor and we use a battery of a car.

So every component in this circuit should resist the high current or all the circuit will be burn out in few seconds.

Another problem is that the PCB routes width increases as the current pass through it increases, so we decided to use wires to connect the components to guarantee that the circuit will not fail under any circumstances.

The high current make us use rough wires with big cross sections to withstand any increase in current, and for this wires it was difficult to connect between the legs of the mosfets and the wires but with some trials we finally solder the wires to the mosfets legs.

Very important note in this area is that the wires should not have a contact with the MOSFETs ( as they are heat up during circuit operation) as or you will find the wires burned out and you will smell bad smokes, and that happens with us in the first making of our circuit.

After soldering the wires to the mosfets legs you should fix the wires very good as the wires may broke down the legs of the mosfets as it is very small in comparison with the cross section of the wires.

We use high power Rosetta to connect between the wires of our circuit as the small Rosetta is not computable for our needs and with high current values it will be damaged.

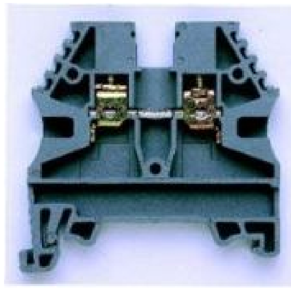


*Fig 5.26.High Power Rosetta*

We find that it connects same points. This helps us a lot to make the shown circuit as we have no holes in our PCB as we see in the figure below. In this circuit no PCB routes all connections used are wires connected to each others.

6) *Module 2 Real Circuit:*

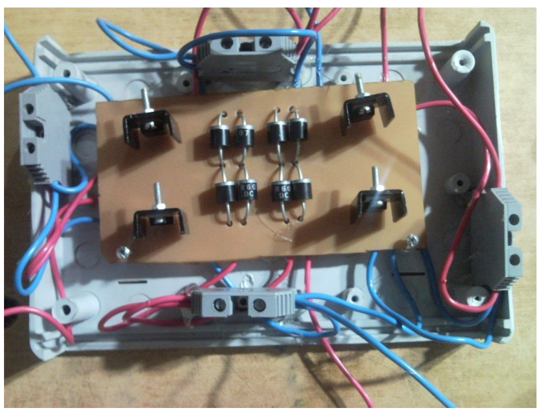


*Fig 5.27.Module 2 Real Circuit*

If we look at the design circuit we will find we use Rosetta J1 & J2 to connect every point to each other and if we look at the real image we will find four Rosetta used and the reason is that every Rosetta we used represent one point so we need four Rosetta as we need four points.

After making the circuit we test it with high current source to make sure it will resist and it works appropriately but the mosfets became more hot and hot so we mount fans to cool the MOSFETs.

7) *And this is the complete circuit configuration:*

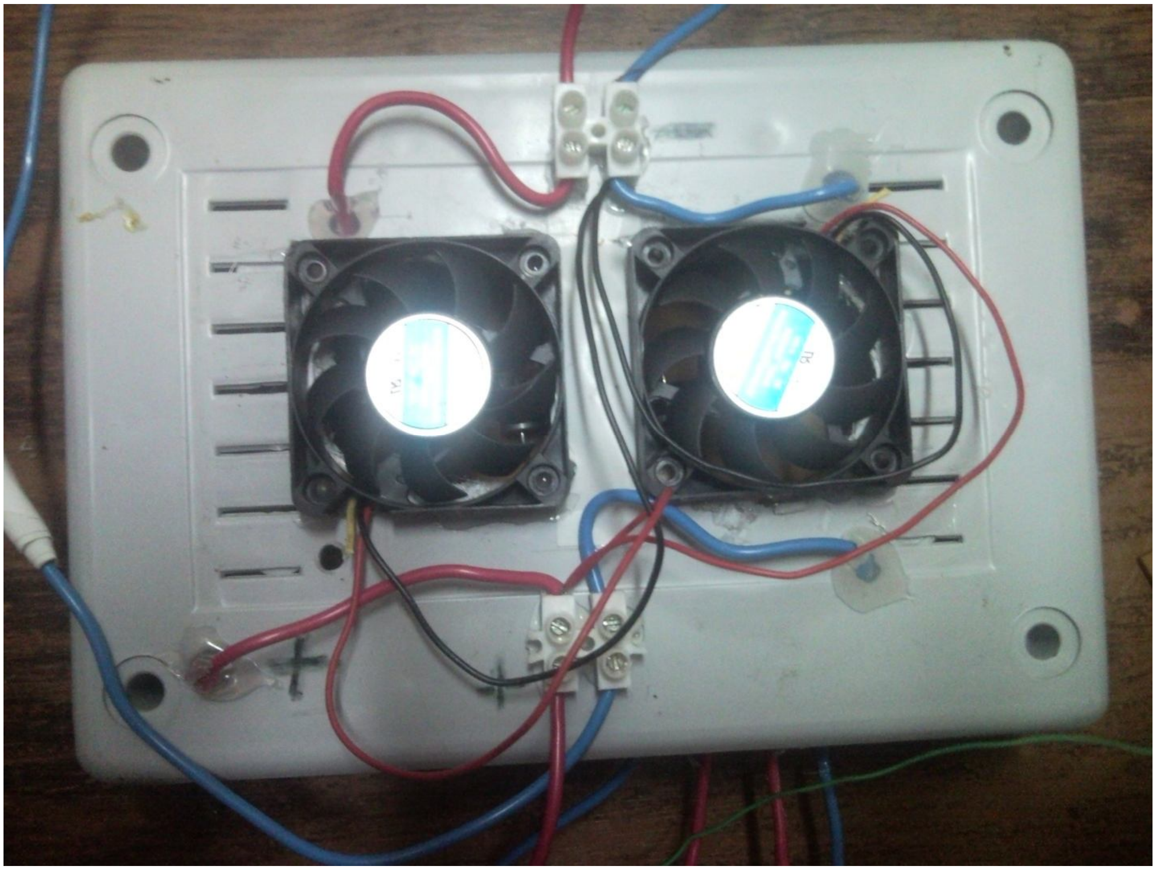


*Fig 5.28.Complete H-Bridge Circuit Configuration*

We make the fans power is the same power of the motor power to make sure that the power is on in the circuit and when the current runs through the mosfets the fans are on and operates well.

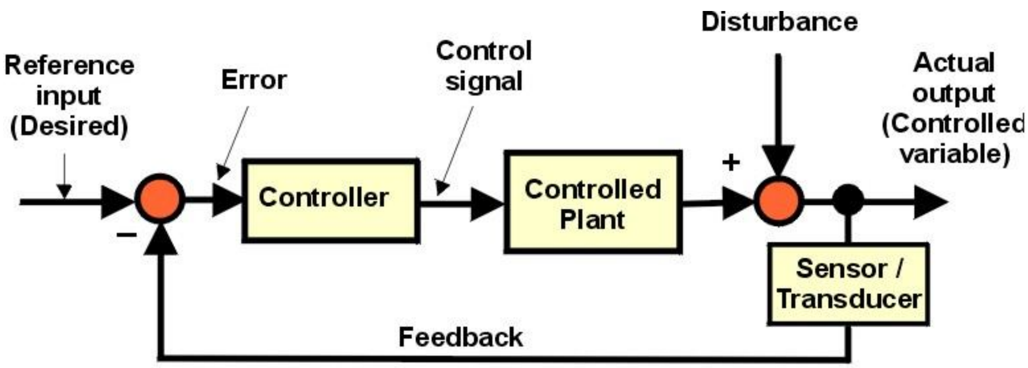
***A question*** is being asked now why we make all this safety for our circuit and the answer that the only reason is the **high current**, we try several times to make smaller circuits but we failed as in every time it burned out so if you are going to make the same circuit with the high current values you should take care of all these things.

***Finally,*** the protection of the H-Bridge could be done easily using a fuse.

In our system we are exposed to face over loading due to any obstacles or any unexpected accidents and that may make the motor drain more current from the battery, making the circuit hot and may cause the mosfets to fail so we use this fuse to prevent more current comes to the motor and to the circuit so we make a security gate for the motor and for the mosfets .

*Fig 5.29 Fuse*

# Chapter 6




Feedback control system

# Control

# PART TWO

# CHAPTER 6

## 6.1. Introduction:

The main concern of this chapter is the design process of the control system used in the project.

It's also concerned by the selection process done so that the control system was built as simple as possible.

During this part of the design process, the mechanical system main features have to be finished and the basic configuration of the power amplification circuit must be done, so that the inputs and outputs from and to the system are listed and known to the designer.

## 6.2. Type of sensors/transducers:

### 6.2.1. Requirements in the sensor we will use:

The sensor we are going to use must have the following:

1. Converts the mechanical rotation angle to a signal that can be read through the microcontroller (voltage signal: analog/digital).
2. Have a medium accuracy and sensitivity.
3. Allow more than 360 degree turn.
4. Easy to use.
5. Won't need a special complicated circuit.

And according to the requirements there are a lot of options and they are:

1. Potentiometer
2. Incremental Encoder

### 6.2.2. Potentiometer as an angle sensor:

*Fig 6.1 Potentiometer*

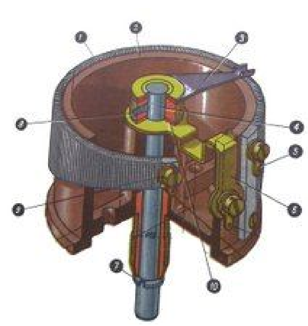


*Fig 6.2 Potentiometer construction*

A potentiometer is a three-terminal resistor with a sliding contact that forms an adjustable voltage divider. If only two terminals are used (one side and the wiper), it acts as a variable resistor or rheostat.

Potentiometers can be obtained with either linear or logarithmic relations between the slider position and the resistance (potentiometer laws or "tapers"). A letter code ("A" taper, "B" taper, etc.) may be used to identify which taper is intended, but the letter code definitions are variable over time and between manufacturers.

*Configurations tested:*

So when we thought about using potentiometers we decided to use it as a potential divider not as a varistor, however we also considered using it as a varistor.

Any way in the two cases we thought of using operational amplifier as a buffer so that the load has approximately no effect on the reading.

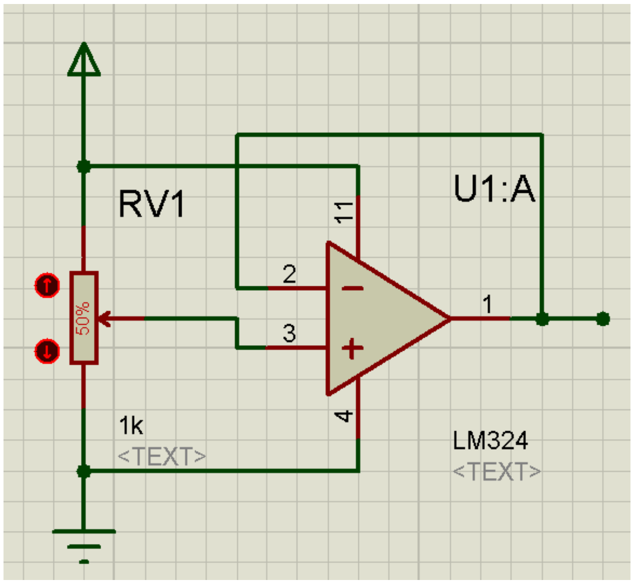



*Fig 6.3 voltage divider with a buffer Circuit*

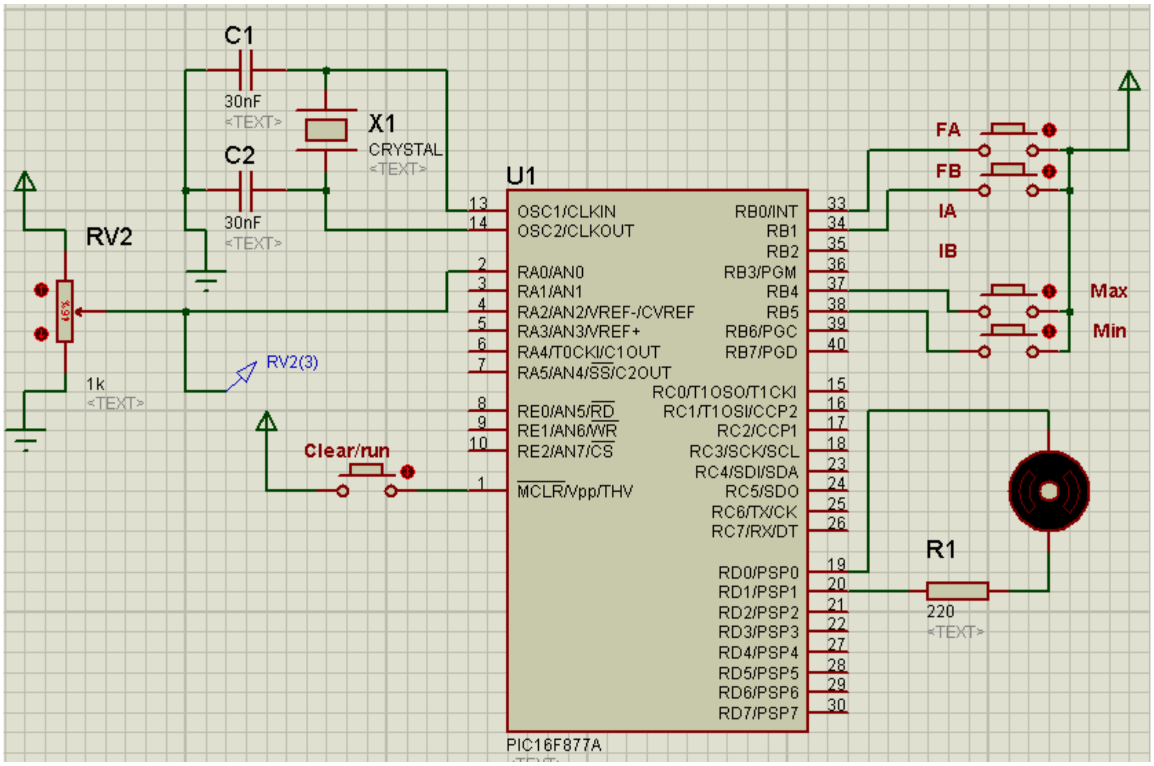



*Fig 6.4 simulating the analog to digital port input from the potentiometer*

<u>Problem we face with potentiometer:</u>

- Sensitivity of incremental encoder is higher than potentiometer.
- There are non linearity in the potentiometer that cause problems where reading.
- Using potentiometer require us to use the analog-to-digital device in the microcontroller with the potential divider circuit which will complicate the code of the microcontroller.
- Using the potentiometer require an additional circuit which will complicate the connections.

### *6.2.3. Incremental encoder:*

#### *6.2.3.1.Brief Description:*

An incremental rotary encoder, also known as a quadrature encoder or a relative rotary encoder, has two outputs called quadrature outputs. They can be either mechanical or optical. In the optical type there are two gray coded tracks, while the mechanical type has two contacts that are actuated by cams on the rotating shaft. The mechanical type requires de-bouncing and is typically used as digital potentiometers on equipment including consumer devices

*Fig 6.5 Incremental encoder*

The fact that incremental encoders use only two sensors does not compromise their accuracy. One can find in the market incremental encoders with up to 10,000 counts per revolution, or more.

*And for this reason we have chosen to use incremental encoders as input and feedback sensors.*

*There can be an optional third output: reference, which happens once every turn. This is used when there is the need of an absolute reference, such as positioning systems.*

The optical type is used when higher RPMs are encountered or a higher degree of precision is required.

Incremental encoders are used to track motion and can be used to determine position and velocity. This can be either linear or rotary motion. Because the direction can be determined, very accurate measurements can be made.

#### *6.2.3.2. Theory of operation:*

They employ two outputs called A & B which are called quadrature outputs as they are 90 degrees out of phase.

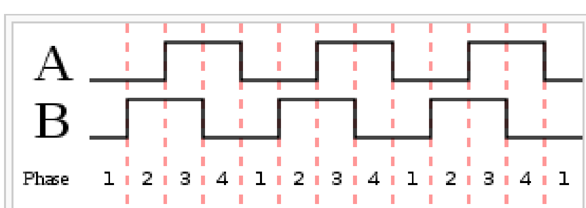



*Fig 6.6 Two square waves in quadrature (clockwise rotation)*

The two output wave forms are 90 degrees out of phase, which is all that the quadrature term means. These signals are decoded to produce a count up pulse or a count down pulse. For decoding in software, the A & B outputs are read by software, either via an interrupt on any edge or polling, and the above table is used to decode the direction. For example if the last value was 00 and the current value is 01, the device has moved one half step in the clockwise direction. The mechanical types would be de-bounced first by requiring that the same (valid) value be read a certain number of times before recognizing a state change.

If the encoder is turning too fast, an invalid transition may occur, such as 00->11. There is no way to know which way the encoder turned; if it was 00->01->11, or 00->10->11.

If the encoder is turning even faster, a backward count may occur. Example: consider the 00->01->11-> 10 transitions (3 steps forward). If the encoder is turning too fast, the system might read only the 00 and then the 10, which yields a 00-> 10 transitions (1 step backward).

This same principle is used in ball mice to track whether the mouse is moving to the right/left or forward/backward.

Rotary sensors with a single output are not encoders and cannot sense direction, but can sense RPM. They are thus called tachometer sensors.

*So, Incremental Encoder is a reasonable device for our system with great accuracy.*

*And this is the photo of our purchased incremental encoder( Its datasheet in the APENDIX)*

*Fig 6.7.Our Purchased incremental encoder*

## 6.3. C-Code:

This part includes the C-code for the controller and for understanding the encoders' readings (and the limit switches too).

Hint: Two limit switched are used to let the micro-controller receive a signal when the wheels reaches one of the two extreme positions while steered. This help us to not stall the motor which means protecting it and the H-Bridge circuit.

*The main steps of the code are:*

1. Include the necessary header files (in embedded C you usually let the editor take care of this part), choose the micro type and the clock configurations.
2. Define the constants you may use during the program.
3. Prototype your functions (if any).
4. Start your program by initializing your variables.
5. Initialize the registers you need in the micro controller.
6. Create your work loop.
    - Read your readings.
    - Understand the meaning of your readings.
    - Let the controller take action.
    - Set your current readings as old readings.
7. End your loop and the program.

### 6.3.1. Header files:

We are using:

- Microcontroller: PIC16F877a.
- Clock: 4 MHz external crystal oscillator.
- Editor: MikroC

So there is no need to add the line

*#include<pic16.h>*

Or any similar lines.

We also don't use special mathematical operations so there is no need to add

*#include<math.h>*

### 6.3.2. Constants used:

We are using two constants:

- limit: to limit the readings from passing the limits of the integer variable they are saved in.
- all_err: to allow error margin, this causes the elimination of the oscillations.

### *6.3.3. Prototypes of the functions:*

In the early versions of the program we used three functions:

- void runmotorsCW(); : Runs the motor in the CW direction.
- void runmotorsCCW(); : Runs the motor in the CCW direction.
- void breakmotors(); : Brakes the motor.

But in the final version we eliminated them for faster program operation.

### *6.3.4. Main function:*

The variables we are using are:

- I, F and X: those will hold the input reading, the feedback reading and the error reading respectively.
- IA, IB, FA and FB: those will hold the recent readings for the phases of each encoder.
- IA0, IB0, FA0 and FB0: those will hold the old readings for the phases of each encoder.
- max and min: will hold the status of the limit switches.

And these variables will have hardware micro pins equivalents which are:

  - FA=RB0;
  - FB=RB1;
  - IA=RB2;
  - IB=RB3;
  - max=RB4;
  - min=RB5;
  - RD0: Motor control pin 1
  - RD1: Motor control pin 2

### *6.3.5. The microcontroller registers that need to be adjusted:*

You must include these two lines in your code so that the input/output functions of the ports work perfectly.

*TRISB=0b11111111;*

*TRISD=0b00000000;*

Those two registers configure PORTB as input and PORTD as output.

### *6.3.6. The working loop:*

We are using an infinite "while loop" to hold the repeated steps of the program.

```
while(1)
{
        // Code of the controller
}
```

#### *6.3.6.1. Reading the encoders reading:*

```
FA=PORTB.F0;
FB=PORTB.F1;
IA=PORTB.F2;
IB=PORTB.F3;
max=PORTB.F4;
min=PORTB.F5;
```

This part reads the encoders and the limit switches status so that it can be compared to the old one, and then a decision is made by the controller.

#### *6.3.6.2. Realizing the encoders' readings:*

```
//Realize the encoders reading
      //input encoder
      if((IA==0 && IBO==1)||(IA==1 && IBO==0))
      {
          if(IA!=IAO || IB!=IBO)      //No change cause no increment
          {
                if(max==0)   //at the end keep booth reading constant
                {
                  I++;
```

```
            }else
                {
                        I=F;
                }
        }
}
else
{
        if(IA!=IAO || IB!=IBO)      //No change cause no decrement
        {
            if(min==0)   //at the end keep booth reading constant
            {
             I--;
            } else
                {
                        I=F;
                }
        }
}
//feedback encoder
if((FA==0 && FBO==1)||(FA==1 && FBO==0))
{
        if(FA!=FAO || FB!=FBO)
        {
            if(max==0)   //at the end keep booth reading constant
```

```
                {
                 F++;
                } else
                        {
                                  I=F;
                        }
         }
}
else
{
         if(FA!=FAO || FB!=FBO)
         {
                if(min==0)   //at the end keep booth reading constant
                {
                 F--;
                } else
                        {
                                  I=F;
                        }
         }
}
```

This part of the code is responsible of converting the changes of the encoders' status to single reading of each encoder.

//This part is done to limit the values of I and F

```
if(I>=limit || F>=limit)
{
```

```
            I=I-limit;
            F=F-limit;
      }
      if(I<=-limit || F<=-limit)
      {
            I=I+limit;
            F=F+limit;
      }
```

### 6.3.6.3. The controller code:

```
//Make the decision about the motor based on the readings
      X=I-F;
      if(X>all_err)
      {
         if(max==0)   //or if(max==1) depending on the sensing config.
         {
            runmotorsCW();       //run the motor CW
         }
         else
         {
            breakmotors();       //brake the motor
         }
      }else if(X<-all_err)
      {
         if(min==0)   //or if(min==1) depending on the sensing config.
         {
```

```
        runmotorsCCW();      //run the motor CCW
      }
      else
      {
        breakmotors();       //brake the motor
      }
    }else
    {
        breakmotors();       //brake the motor
    }
```

Where this kind of code can achieve the function of on/off control with a margin of error that eliminates or reduces the oscillations.

Also the functions "*runmotorsCW();*", "*runmotorsCCW();*" and" *breakmotors();*" are simply putting one or zero on the control pins: RD0 and RD1.

```
//Put the recent encoder readings as the old one
    FAO=FA;
    FBO=FB;
    IAO=IA;
    IBO=IB;
```

### 6.3.6.4 Full controller code:

```
/*This is the micro code
and those are the pins used from the micro:
      FA=RB0;
      FB=RB1;
```

```
        IA=RB2;
        IB=RB3;
        max=RB4;
        min=RB5;
        RD0: Motor control pin 1
        RD1: Motor control pin 2
*/
//Define here the constants that you will use for the program
#define limit 32000
#define all_err 20

//Main function
int main(void)
{
  //Initialize the variables you will use
  int I=0,F=0,X=0;
  /*
  this variables will hold:
     I: input realized signal
     F: feedback signal
     X: error signal
  */
  int IA=0,IB=0,IAO=0,IBO=0;
  /*
  this variables will hold:
```

```
    IA: input encoder recent phase 1 signal
    IB: input encoder recent phase 2 signal
    IAO: input encoder old phase 1 signal
    IBO: input encoder old phase 2 signal
*/
int FA=0,FB=0,FAO=0,FBO=0;
/*
this variables will hold:
    FA: feedback encoder recent phase 1 signal
    FB: feedback encoder recent phase 2 signal
    FAO: feedback encoder old phase 1 signal
    FBO: feedback encoder old phase 2 signal
*/
int max=0,min=0;
/*
this variables will hold:
    max: limit switch value (0 if not pushed)
    min: limit switch value (0 if not pushed)
*/
 //Initialize the micro registers here
TRISB=0b11111111;
TRISD=0b00000000;
//Get the intial values for the encoders reading
        FAO=PORTB.F0;
        FBO=PORTB.F1;
```

```
        IAO=PORTB.F2;
        IBO=PORTB.F3;
        max=PORTB.F4;
        min=PORTB.F5;
//brake the code
PORTD.F0=PORTD.F1=0;    //brake the motor
while(1)
{
    //Read the encoders reading
        FA=PORTB.F0;
        FB=PORTB.F1;
        IA=PORTB.F2;
        IB=PORTB.F3;
        max=PORTB.F4;
        min=PORTB.F5;
    //Realize the encoders reading
    //input encoder
    if((IA==0 && IBO==1)||(IA==1 && IBO==0))
    {
        if(IA!=IAO || IB!=IBO)    //No change cause no increment
        {
            if(max==0)  //at the end keep booth reading constant
            {
             I++;
            }
```

```
                else
                {
                I=F;
                }
        }
}
else
{
        if(IA!=IAO || IB!=IBO)      //No change cause no decrement
        {
                if(min==0)   //at the end keep booth reading constant
                {
                  I--;
                }
                else
                {
                I=F;
                }
        }
}

//feedback encoder
if((FA==0 && FBO==1)||(FA==1 && FBO==0))
{
        if(FA!=FAO || FB!=FBO)
```

```
        {
                if(max==0)   //at the end keep booth reading constant
                {
                  F++;
                }
        }
}
else
{
        if(FA!=FAO || FB!=FBO)
        {
                if(min==0)   //at the end keep booth reading constant
                {
                  F--;
                }
        }
}
//This part is done to limit the values of I and F
if(I>=limit || F>=limit)
{
          I=I-limit;
          F=F-limit;
}
if(I<=-limit || F<=-limit)
{
```

```
        I=I+limit;
        F=F+limit;
    }
    //Make the decision about the motor based on the readings
    X=I-F;
    if(X>all_err)
    {
      if(max==0)   //or if(max==1) depending on the sensing confg.
      {
        PORTD.F0=1;
              PORTD.F1=0;        //run the motor cW
      }
      else
      {
        PORTD.F0=PORTD.F1=0;        //brake the motor
      }
    }else if(X<-all_err)
    {
      if(min==0)   //or if(min==1) depending on the sensing confg.
      {
        PORTD.F0=0;
              PORTD.F1=1;      //run the motor ccw
      }
      else
      {
```

```
            PORTD.F0=PORTD.F1=0;        //brake the motor
          }
        }
        else
        {
            PORTD.F0=PORTD.F1=0;        //brake the motor
        }
        //Put the recent encoder readings as the old one
        FAO=FA;
        FBO=FB;
        IAO=IA;
        IBO=IB;
        //give the code some delay
        Delay_1us();
   }
   return(0);
}
```

## 6.4. Simulation Circuit

We moved then to the simulation Circuit on Proteus and it works properly.

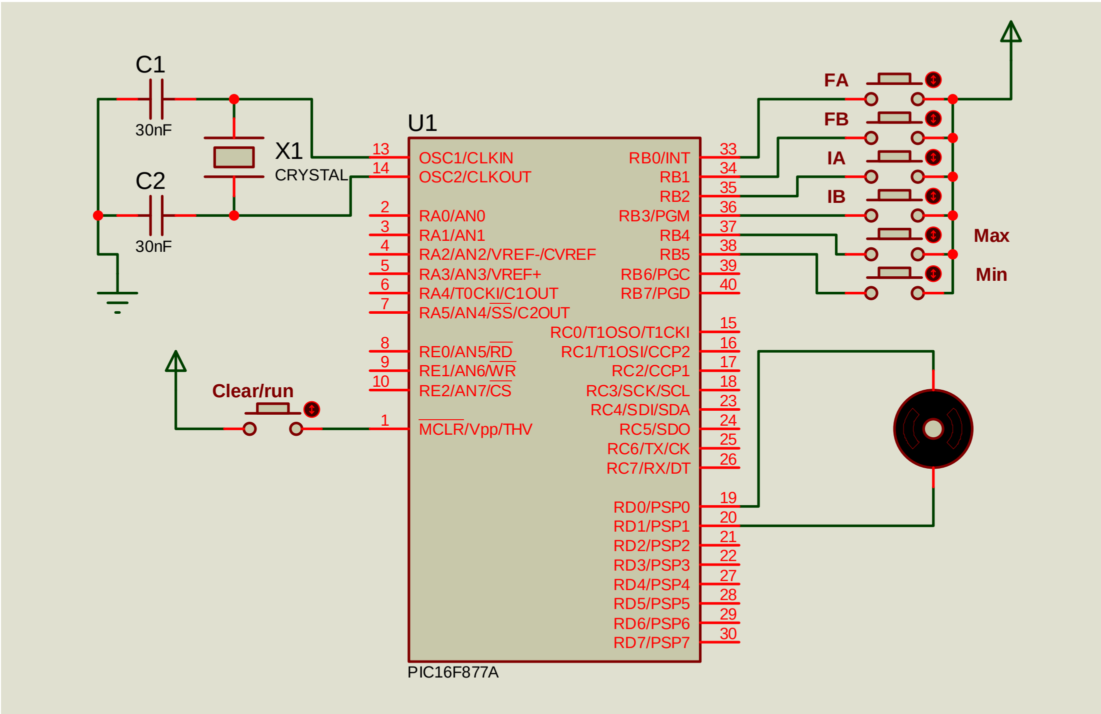



*Fig.6.8. Simulation Circuit*

As shown in the above figure we simulated every encoder as two input switches. And the circuit works.

## 6.4. Main Brain Control Circuit design:

After wards we began to design the main brain circuit that will receive two input signals from the every encoder and also two input signals from every limit switch and will output 2 signals to control the H-Bridge.

***Hint:*** As mentioned before we are going to use PIC 16F877A as micro-controller in the control circuit.

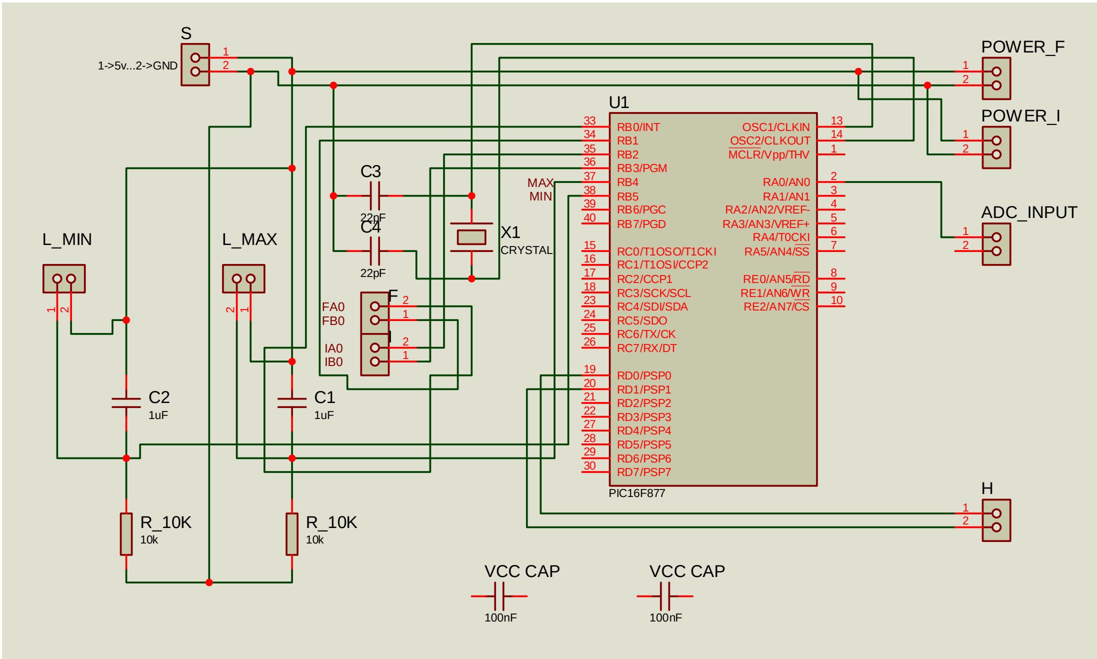



*Fig.6.9. Main Brain Circuit Schematic*

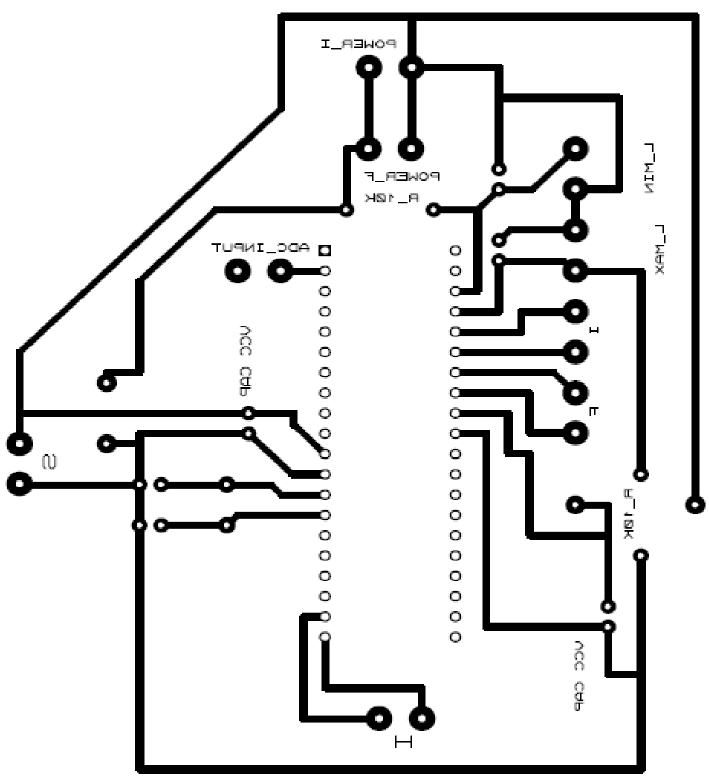


*Fig.6.10. Main Brain Circuit Schematic*

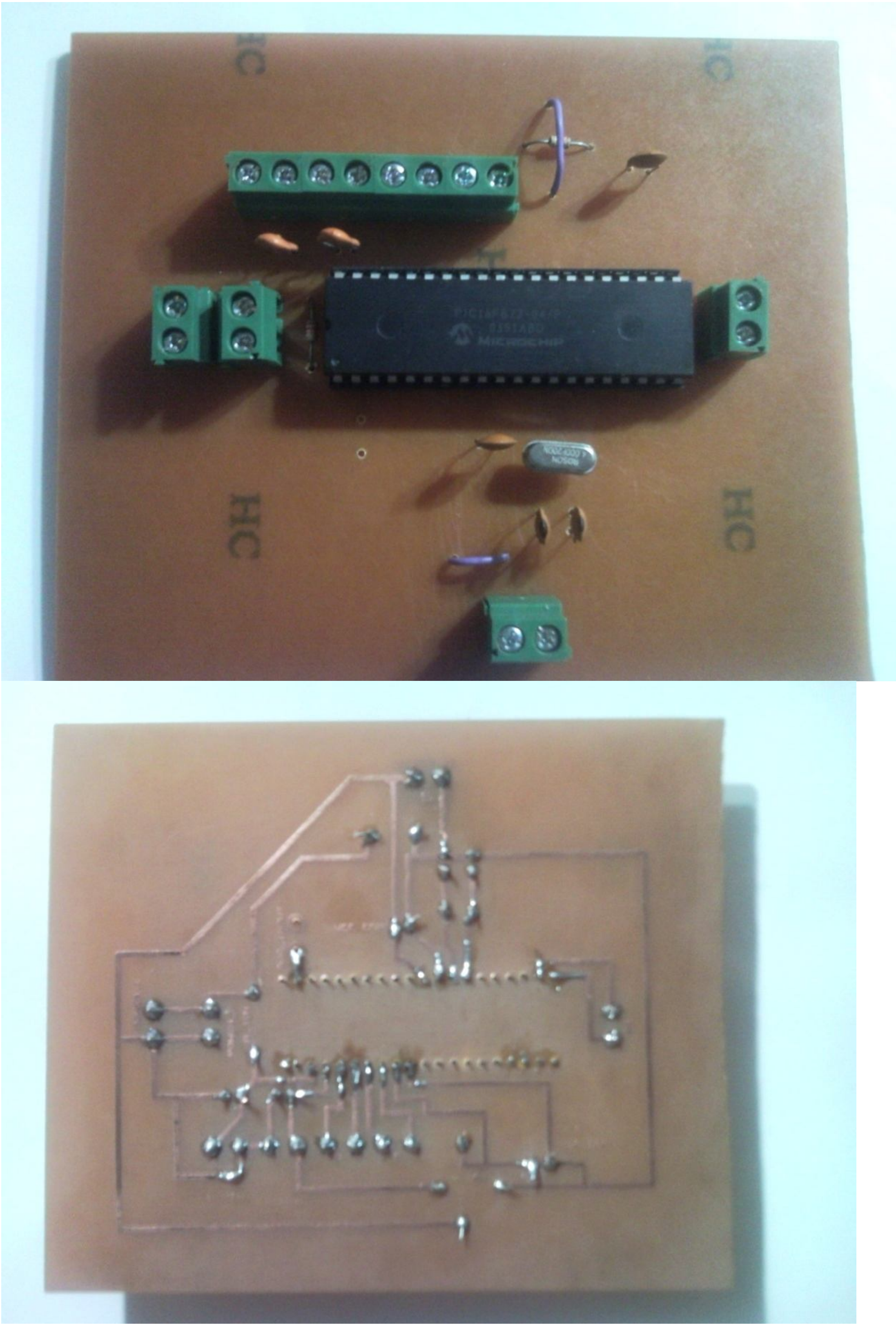


*Fig.6.11. Main Brain Real Circuit*

*Then we designed a small indicators circuit that has 5 LEDS as follows:*

1. *POWER ON*
2. *Turning the input encoder in one direction*
3. *Turning the input encoder in the other direction*
4. *Limit Switch 1*
5. *Limit Switch 2*

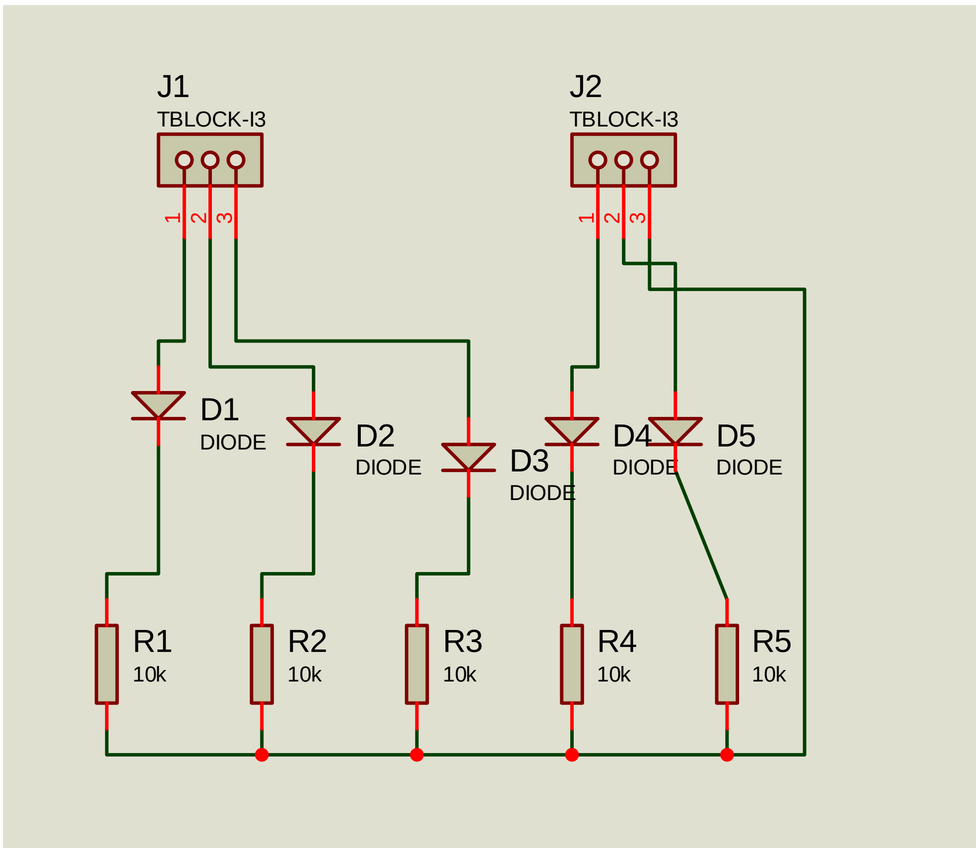



*Fig.6.12. Indicators Circuit Layout*

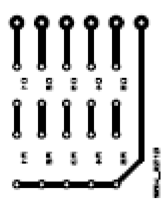


*Fig.6.13. Main Brain Circuit PCB layout*

*This circuit helped us to test the main brain circuit separately from H-Bridge Module.*

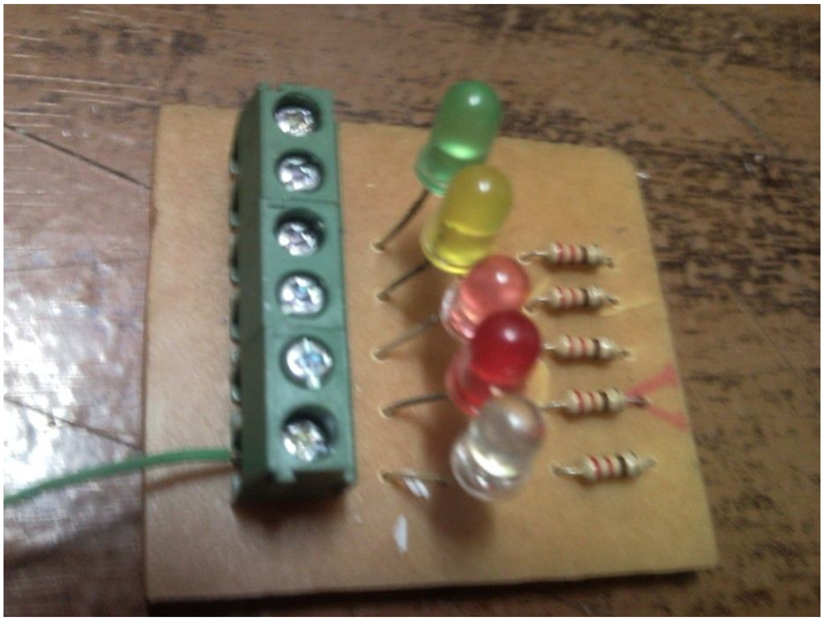
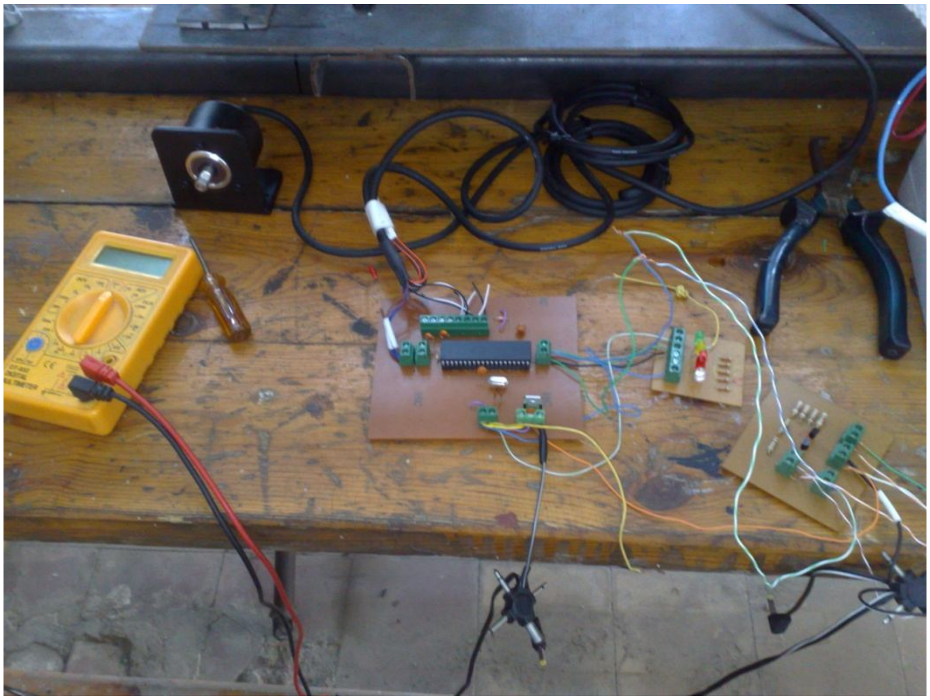


*Fig.6.14. Indicators Real Circuit*

*Then the whole system is ready to be tested and this is what we will figure out in the next chapter.*

# Chapter 7



# Testing

# CHAPTER 7

## 7.1. Testing Preparations:

Before testing the whole system, we made some boxes for the electrical circuits.

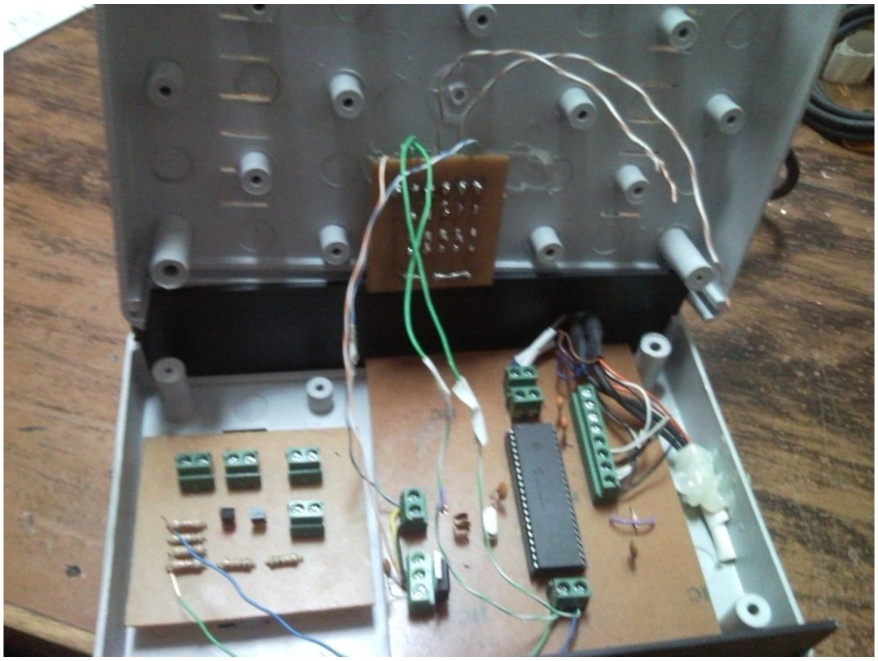


*Fig 7.1.The left one is the H-Bridge Control Circuit, while the other circuit Main Brain Circuit*

*Fig 7.2.RJ connectors to simplify the connection process*

## 7.2. Testing Preparations:

Afterwards, we began to prepare the test bench

*Fig 7.3.Test Work Bench Preparation*

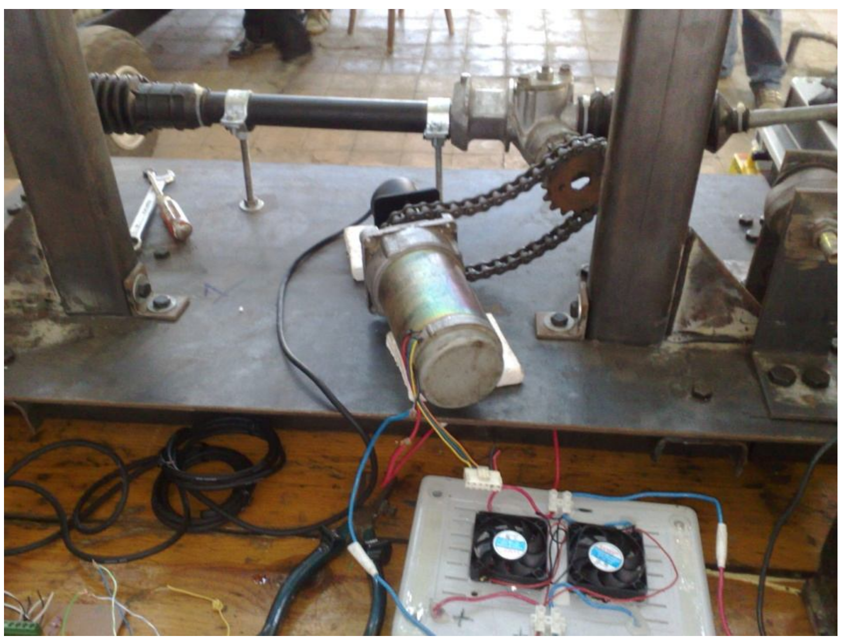


*Fig 7.4.Test Work Bench Preparation*

*Fig 7.5.Test Work Bench Preparation*

## 7.3. Problems we faced while testing:

*The problem of oscillations of the motor:*

While testing the early versions of the code we faced this situation:

- *First Remark:* The motor tries to reach its set point but it can't stop at this set point so it continues oscillation forever.
- *Second Remark:* is that when the motor is loaded the oscillations are limited and may damp and after a long time the motor may reach its set point or continue oscillating put with smaller amplitude.

### 1. Explanation of this phenomenon:

-For a clear explanation of this phenomenon we must describe it in more details by the following graph; that describes the ***first remark*** about this situation:

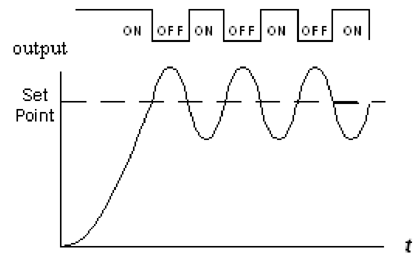



*Fig 7.6.Oscilliation Phenomenon (The change of the output compared to the control action coming from the controller)*

The next graph describes the second remark of this situation:

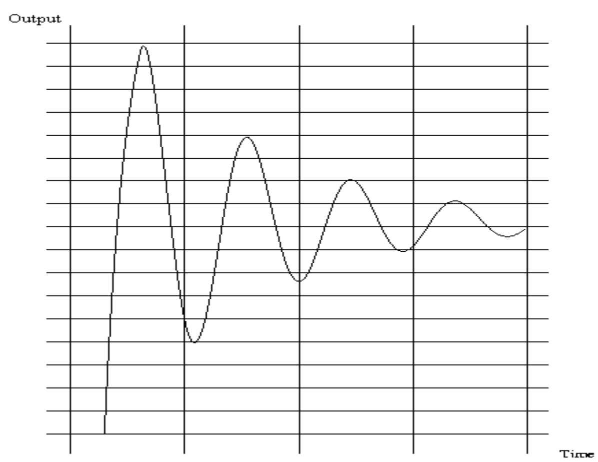



*Fig7.7. the curve describing the second situation*

*And we also must look into the controller code which is the reason for this problem:*

*//Make the decision about the motor based on the readings*

```
X=I-F;

if(X>0)

{

    if(max==0)   //or if(max==1) depending on the sensing config.

    {

       runmotorsCW();        //run the motor CW

    }

    else
```

```
    {
      breakmotors();       //brake the motor
    }
}else if(X<0)
{
    if(min==0)   //or if(min==1) depending on the sensing config.
    {
      runmotorsCCW();     //run the motor CCW
    }
    else
    {
      breakmotors();       //brake the motor
    }
}else if(X==0)
{
      breakmotors();       //brake the motor
}
```

*2. The detailed reasoning of this problem:*

The controller acts as the following graph:

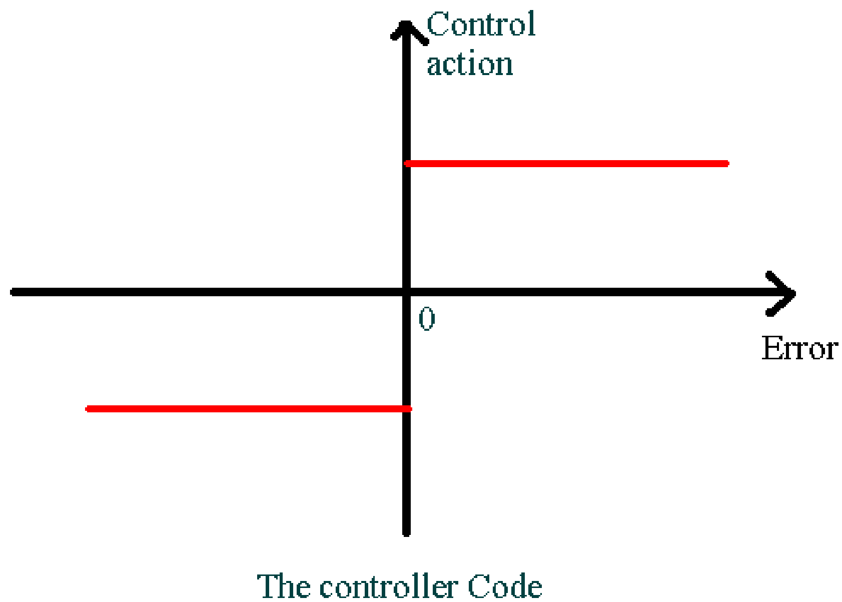



*Fig7.8. the controller code before modifications*

So due to that the speed of the motor when reaching the zero error point is maximum and we want it to break immediately, and due to its inertia it continue moving and pass the zero error point.

Now the motor is decreasing its speed and then reversing its direction to return to the zero error point and simply there is no guarantee that the motor will reach the zero error point in a zero speed and this cause the oscillations to continue forever.

***Now to the second remark:***

When the motor is loaded it is affected by a load that limits the speed of the motor and then the inertia of the motor with load makes it harder to stop in time but it also don't allow a fast change in the speed after passing the zero error point so the total result is that the speed decrease after each cycle of oscillations and eventually the motor will come to rest in the zero error point or will continue to oscillate around this point in a very low speed.

## 7.4. Problems Solution:

*The solution to the oscillations problem:*

To solve this problem without making a major change in the controller design we have to add an error margin so that the oscillations are contained in this range and the motor stops.

This can be done by expanding the zero error point into an allowed error zone like this graph:

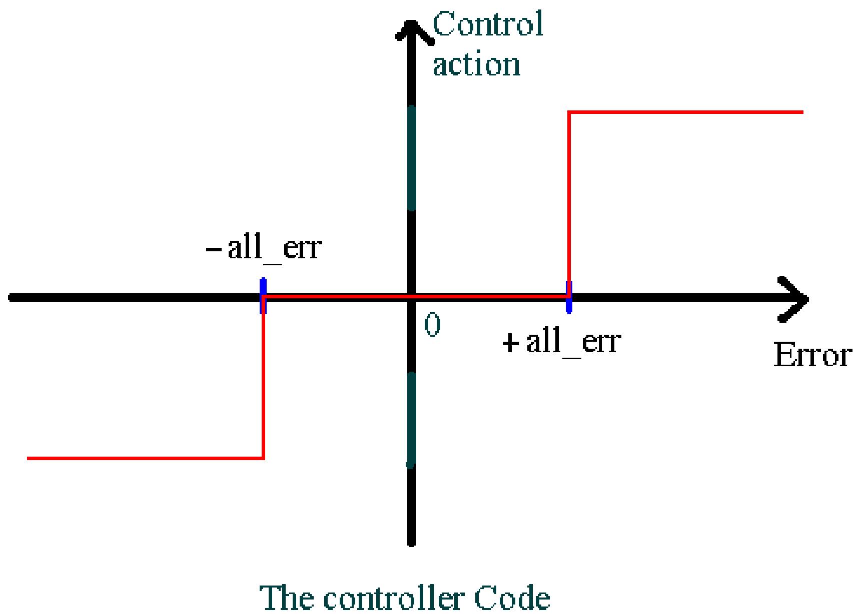



Fig7.9. The controller code after modifications

And the constant (all_err) can be determined by experiments for the optimum on/off controller code.

*2. The code after modifications:*

This is the new controller code:

```
//Make the decision about the motor based on the readings
        X=I-F;
        if(X>all_err)
        {
            if(max==0)   //or if(max==1) depending on the sensing confg.
```

```
    {
     PORTD.F0=1;
            PORTD.F1=0;     //run the motor cW
    }
    else
    {
     PORTD.F0=PORTD.F1=0;     //brake the motor
    }
}else if(X<-all_err)
{
    if(min==0)   //or if(min==1) depending on the sensing confg.
    {
     PORTD.F0=0;
            PORTD.F1=1;     //run the motor ccw
    }
    else
    {
     PORTD.F0=PORTD.F1=0;     //brake the motor
    }
}
else
{
     PORTD.F0=PORTD.F1=0;     //brake the motor
}
```

***After this code modification, the system runs properly as desired, when we steer it right it goes right, when we steer it left it goes left with a reasonable response.***

Also the code can be modified to make the effect of a PID controller using the idea of PWM to control the speed of the motor in addition to the position.

For more information about further modifications that can be done on the code read the future research on Chapter 8.

### *7.5. Verification:*

As we know that Verification means checking whether the way in which something is realized and whether it coincides with the specification or not.

Our system has been designed through VDI 2206, so it coincides with the specification. This is clear in the implementation of the mechanical test bed as it consists of standard parts. Add to this the electrical part and it modeling and simulation step by step.

### *7.6.Validation:*

We know that Validation answers the question whether the product is suitable for its intended purpose or not.

Our system do it task which is steering thw wheels with no mechanical connection between the steering wheel and the road wheels, instead this is done using signals and wires, so the system has succeeded in it mission.

# Chapter 8


# Future Recommendations

# CHAPTER 8

## 8.1. Introduction:

In this chapter we are discussing what can be done in the future to enhance the steer by wire system performance.

We will also consider the possibilities and configurations that this system can have to choose the most efficient system configuration from the safety, simplicity, cost and power efficiency point of view.

The need to develop and add to any product/system is essential to satisfy the customer requirements.

The steer-by-wire system itself is a modification to the traditional steering system, and it is still under development to give a different sense of driving a car, and to apply new technologies to the automotive industry so that it can face the new challenges.

## 8.2. Modifications that can be done on the mechanical system:

The basic design of the mechanical system was made too simple, and also too compatible with the car design, and allows the simulation of different load conditions.

So that it needs no major modifications in its structure.

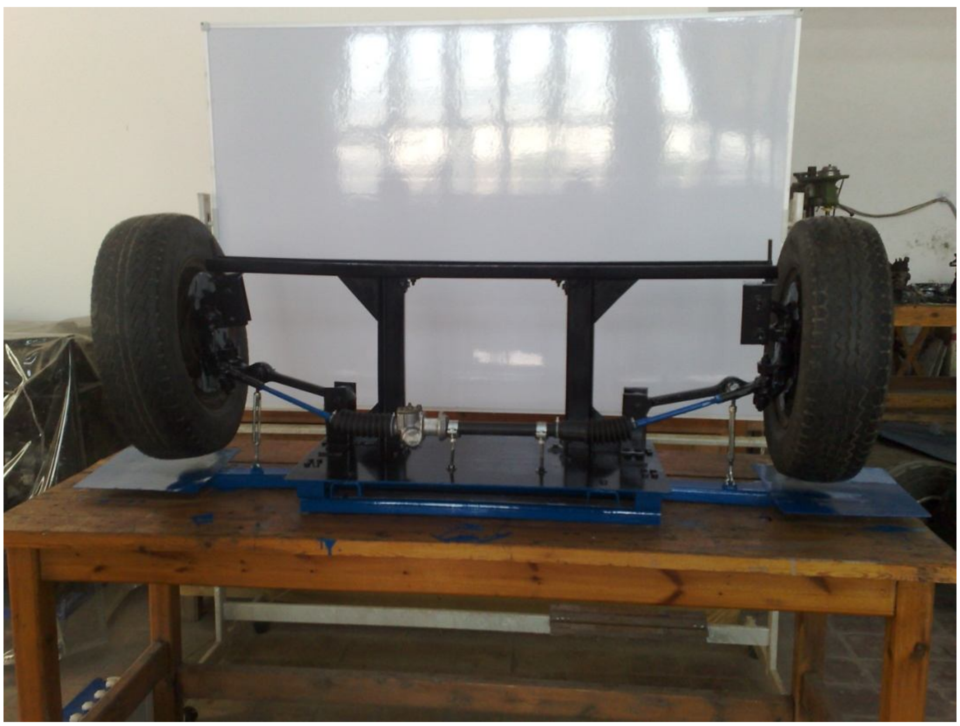


*Fig 8.1 Basic Test Bed*

The only major improvement that can be done on the system is studying the possibility of separating the steering system of each wheel and using different motor for each wheel.

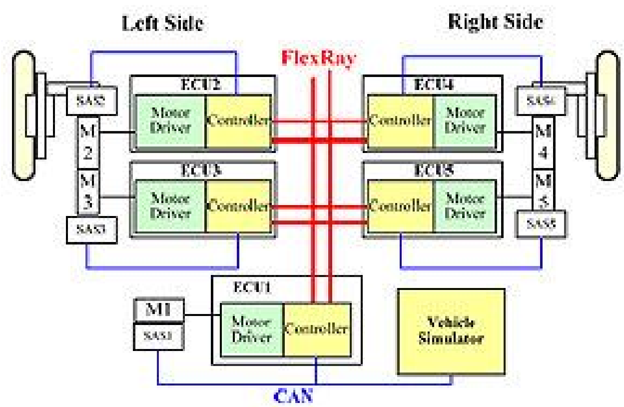
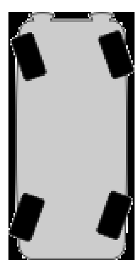



*Fig 8.2 using two motors in steering*

The reason that this may be important is that redundancy is a need for the system to be safer and may be less expensive.

Also this will allow the possibility to study four wheel steering (4WS) which will need more advanced control and more equipments than the single motor steer-by-wire already done.



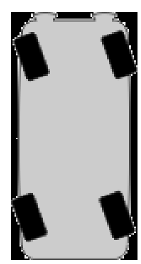


Fig 8.3(a) 4WS in slow speed Fig 8.3(b) 4WS in fast speed

## *8.3. Modifications that can be done on the input and feedback devices:*

### *8.3.1. The input devices:*

In our system we used an incremental encoder as a transducer at the driving wheel.

Fig 8.4 encoders

In the future the possibility of another input device (Transducer) must be considered, as example an angle sensor or a potentiometer or an absolute encoder in place of the incremental encoder.

Fig 8.5(a) potentiometer

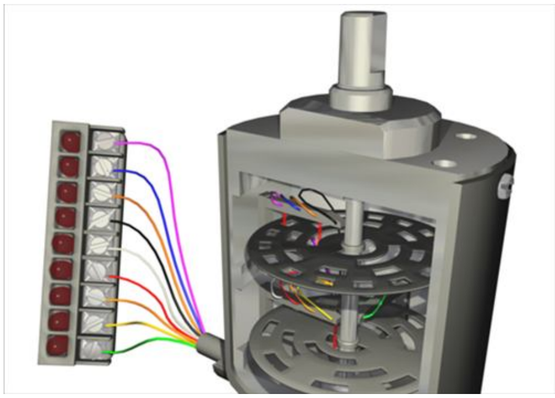


Fig 8.5(b) absolute encoder

Also we must discuss the possibility of using feedback motor or brakes on the input device, so that the driver have a sense of the steering action as well as road conditions.

This will enhance the stability of the steering system and improve the driving capabilities.

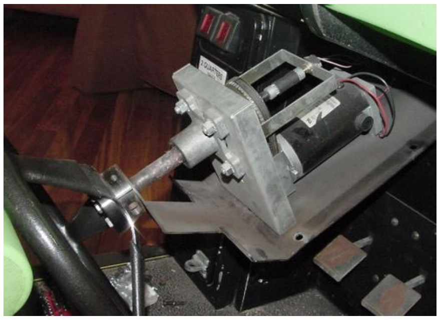


Fig 8.6 Feedback motor on the steering wheel

Also using a joy stick, push buttons as input instead of the driving wheel devices is possible.

### *8.3.2. Actuator*

As we have used a normal DC-Motor as an actuator.And we have used an incremental encoder in the feedback signal to the controller. It is possible to use a servo-motor instead of normal DC-motor and encoder.

Fig 8.7 servo-motors

## 8.4. Modifications that can be done on the power amplification circuit:

We have used a MOSFET based H-bridge, and there is the possibility of using mechanical relays, or power transistors.

Also the possibility of using a motor drive for the motor so that this will decrease the need for complicated electronic circuits.

Fig 8.8 an example of a motor driver circuit

## 8.5. Modifications that can be done on the control circuit:

The control circuit was done to be compatible to changes.

It allows a six digital inputs. And one analog input for a potentiometer if needed and also it is easy to modify.

It contains two de-bounced inputs out of the six that can be used for the limit switches.

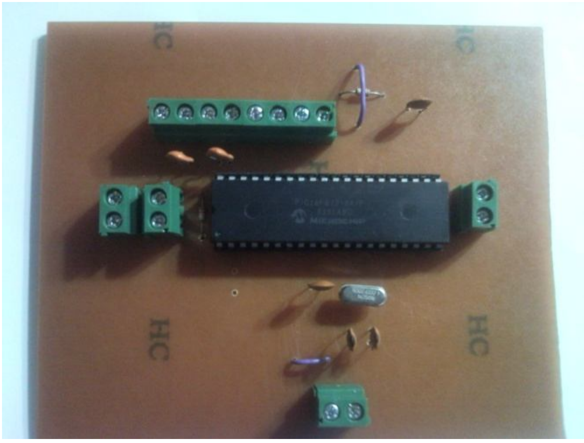


Fig 8.9 the main control circuit

It can be modified so that it contains the signal conditioning for the circuit and the power amplification (or the connections to the driver circuit).

Also the possibility of using a programmable logic controller (PLC) will come with great changes on the system behavior, so it must be considered.

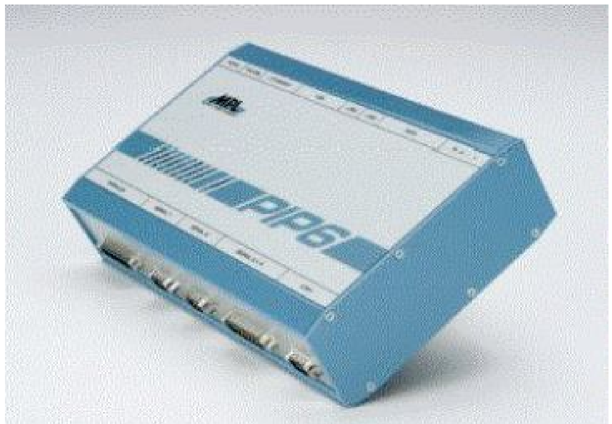


Fig 8.10 PLC

If a PLC circuit is used there will be no need to use a power amplification circuit for the motor, because the motor can work on 24V from the PLC directly or indirectly.

Also the code will be changed into a ladder diagram code which may simplify the code and introduce a different kind of interface that can be used.

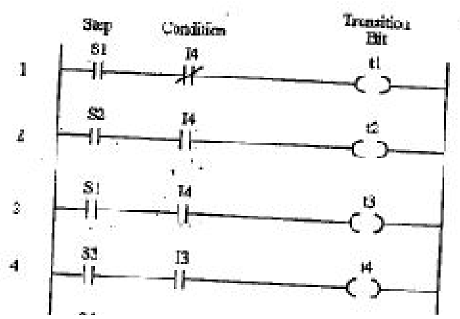


Fig 8.11 Ladder diagram

Also the PLC comes with networking capabilities that may be used in the system.

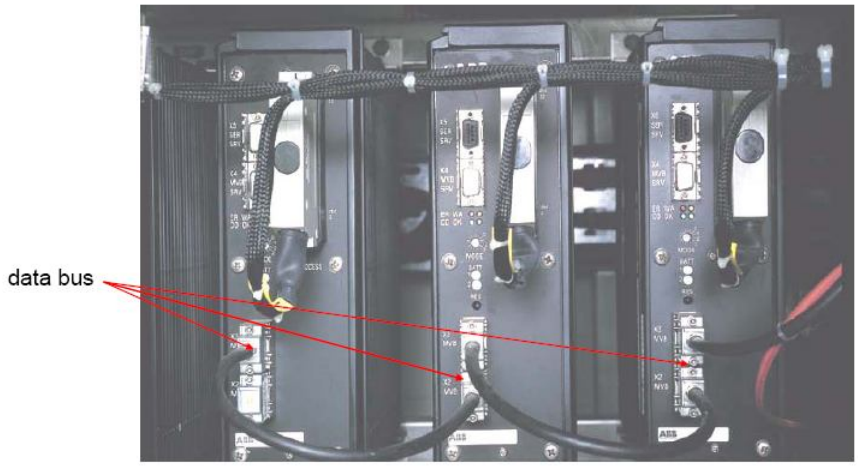



Fig 8.12 Networking using PLC capabilities

***8.6. Modifications that can be done on the controller code:***

The code for the controller works as an on/off controller with error margin, this doesn't completely remove oscillations but reduces it and maintain the system stability.

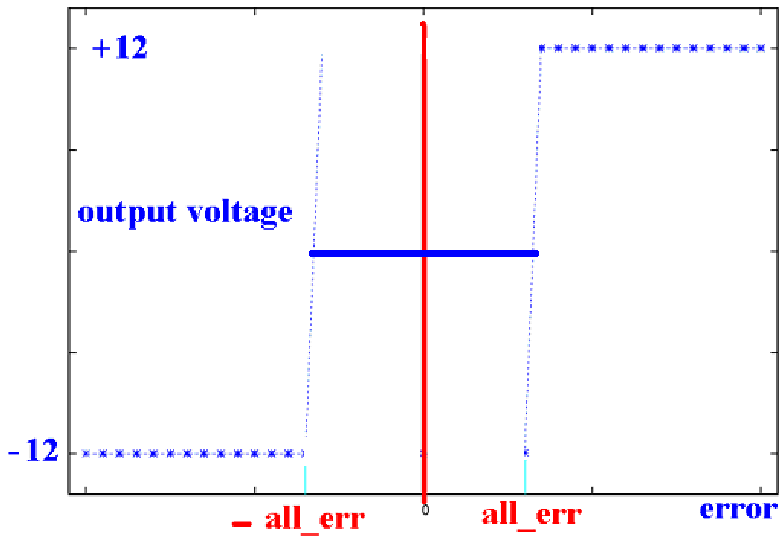



Fig 8.13 on/off control

The controller code can be modified to achieve the function of a PID controller, or we can use the idea of PWM (pulse width modulation).

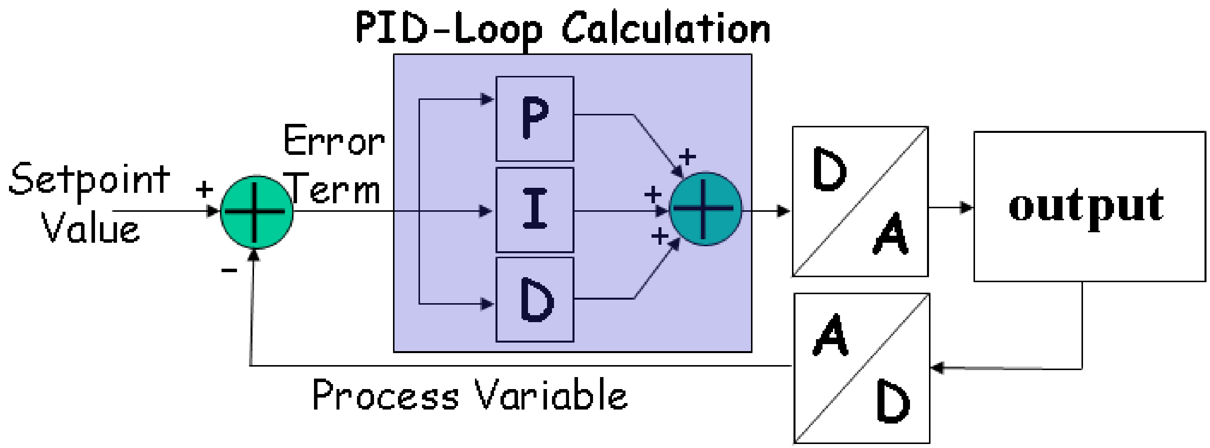



Fig 8.14 block diagram of PID

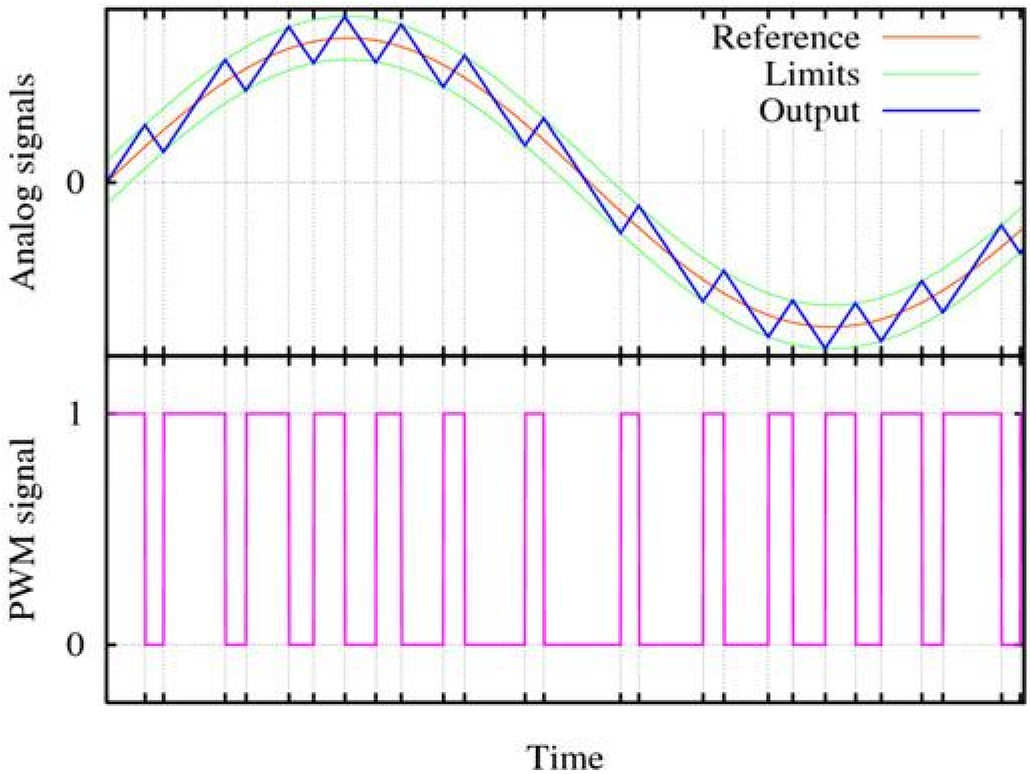



Fig 8.15 PWM signal

Also because of the nonlinearity in the steering system, it may be suitable to use a controller based on the idea of neural networks, it will be useful and adaptable to changes and nonlinearities.

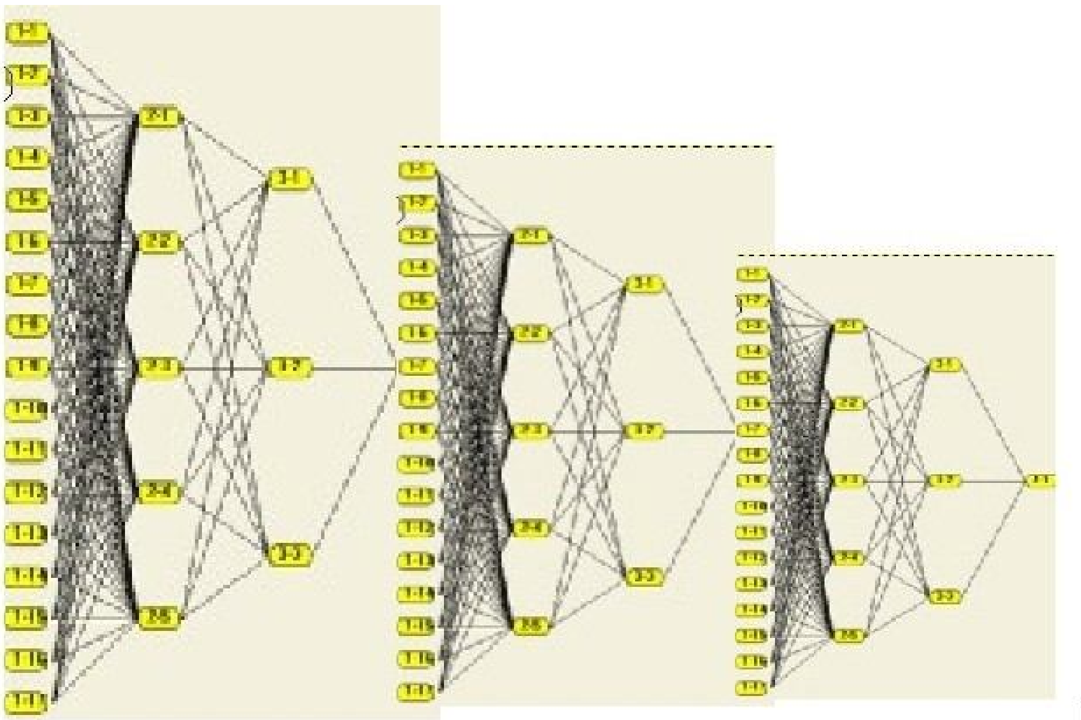


Fig 8.16 neural network

Also an error prediction and treatment code can be added to the controller so that the system will be safer and error tolerant.

## 8.7. Modifications that can be done on the system as whole:

Some fanciful theories and applications abound as to what the ultimate implications of drive-by-wire technology might be. It has been suggested that drive-by-wire might allow a car to become completely separate from its controls, meaning that a car of the future might theoretically be controlled by any number of different control systems: push buttons, joysticks, steering wheels, or even voice commands — whatever device that designers could come up with.

And for this to happen, the car must be converted into networks of systems, all connected and working in harmony to achieve the functionality of the vehicle and make the driving process as easy as possible.

In the very near future, further systems will be added to the vehicle. Although it would be possible to use the same network for many of the new functions, it would not be practical. The additional performance and complexities which are associated with the higher classes of networks are more expensive to implement than the simple Class A networks. It is also more prudent from a safety standpoint to keep non-safety-critical information apart from the networks which support safety critical systems. Already some luxury vehicles have networks which resemble that shown in the figure below.

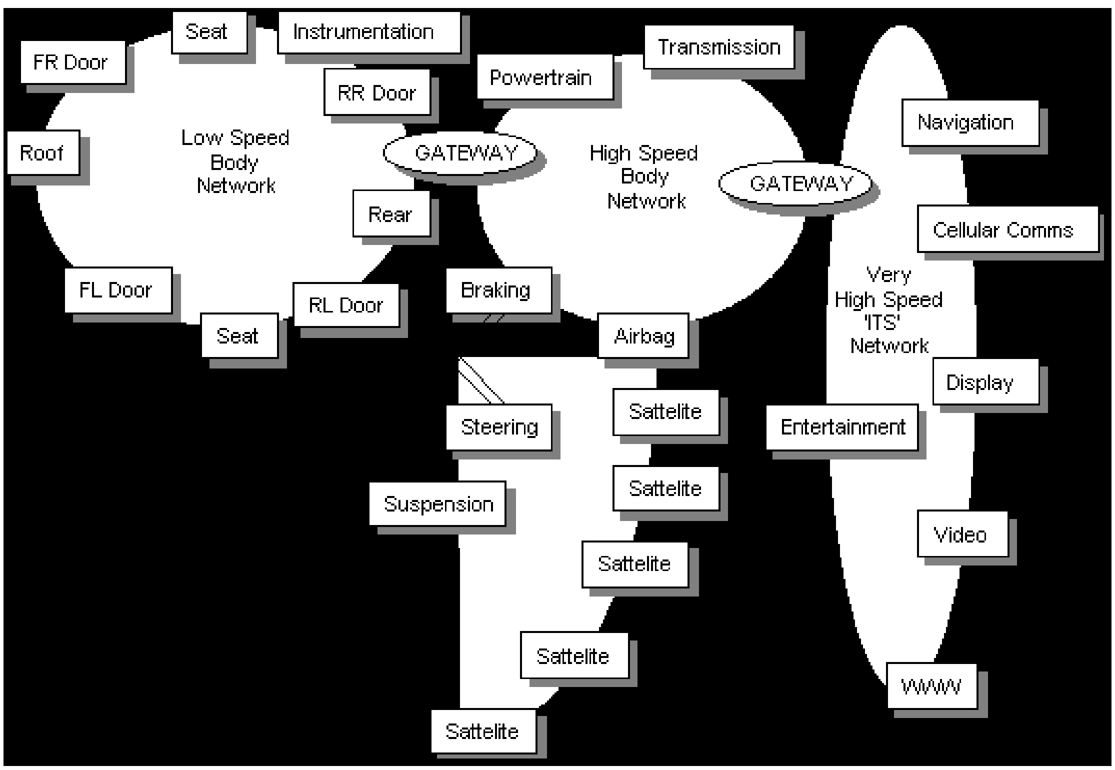



Fig 8.17 advanced Vehicle Multiplexing Requirements

Achieving the drive-by-wire systems are unlimited and the auto driver won't be just a dream but a fact that only needs time to turn from idea to reality.

### ***8.8. Summary:***

Any major change needs the cooperation of persons from more than one field to be achieved.

For more progress in this project the cooperation between automotive engineers and Mechatronics engineers must happen.

For building the future car environmental friendly, power efficient, comfortable, easy to drive and more importantly safer than ever; the work in this project and similar project must continue.

Also the competition between the vehicles companies must continue to provide ideas and modifications, so that all the customer needs are satisfied.

At the end the objective of this project was to prove the concept of the steer-by-wire and prove its capability of replacing the conventional steering systems.

## ***Question:***

***Can a steer-by-wire (SBW) system replace the conventional steering systems?***

## **Answer:**

*YES, IT CAN, and there are still researches that going on for this major jump to happen, and it is only a time factor.*

# ***References:***


**[1]:***http://osg.informatik.tu-chemnitz.de/lehre/old/ws0809/sem/online/x-by-wire.pdf*

**[2]:***www.site.uottawa.ca/~rhabash/RyanGermain.ppt*

**[3]**:*http://www.engin.swarthmore.edu/academics/courses/e90/2005_6/E90Proposal/AK.pdf*

**[4]:***http://www.loria.fr/~nnavet/publi/CRC2005_XbW.pdf*

**Ref 5:***http://ewh.ieee.org/r10/india_council/newsletters/2005/feb05.pdf*

**[6]:***http://www.lag.ensieg.inpg.fr/canudas/publications/Vehicle_control_recent/Steer-bywire_ACC06.pdf*

**[7]:***www.engr.iupui.edu/me/courses/team7.ppt*

**[8]:***http://www.itz.tu-clausthal.de/uploads/media/ITZsteerbywire.pdf*

**[9]:***http://www.kollmorgen.com/website/com/eng/download/document/IUV_Reprint__Steer_by_Wire _Danaher_Motion_JAN_FEB_09_Issue.pdf*

**[10]:***http://www.sae.org/images/books/toc_pdfs/PT140.pdf*

**[11]:** *Stanford, STEER-BY-WIRE IMPLICATIONS FOR VEHICLE HANDLING AND SAFETY, http://wwwcdr. stanford.edu/dynamic/bywire/dissertation.pdf*

**[12]:*http://www.steer-by-wire.info/***

**[13]:*ddl.stanford.edu/files/Presentationv2.ppt***

**[14]:** *[1] Controller design of a new active front steering system, http://ukacc.group.shef.ac.uk/Control_Conferences/Control2006/papers/f225.pdf*

**[15]:** *Direct Current Measurement Based Steer By Wire Systems for Realistic Driving Feeling(TA08-3.pdf, the link is: http://robot.kut.ac.kr/papers/TA08-3.pdf)*

**[16]:** *http://www.carbibles.com/steering_bible.html*

**[17] :** *http://auto.howstuffworks.com/steering2.htm*

# Appendix

# IMPORTANT DATA SHEETS

# P-Channel MOSFET IRF9540N

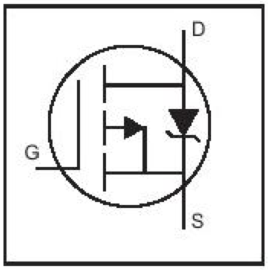
International
IOR Rectifier

PD - 91437B

# IRF9540N

HEXFET® Power MOSFET

- Advanced Process Technology
- Dynamic dv/dt Rating
- 175°C Operating Temperature
- Fast Switching
- P-Channel
- Fully Avalanche Rated




$V_{DSS}$ = -100V

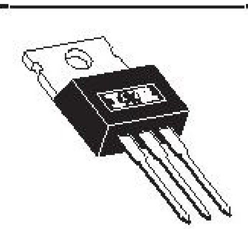
$R_{DS(on)}$ = 0.117Ω

$I_D$ = -23A

## Description

Fifth Generation HEXFETs from International Rectifier utilize advanced processing techniques to achieve extremely low on-resistance per silicon area. This benefit, combined with the fast switching speed and ruggedized device design that HEXFET Power MOSFETs are well known for, provides the designer with an extremely efficient and reliable device for use in a wide variety of applications.

The TO-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry.



TO-220AB

## Absolute Maximum Ratings

| | Parameter | Max. | Units |
|---|---|---|---|
| $I_D$ @ $T_C$ = 25°C | Continuous Drain Current, $V_{GS}$ @ -10V | -23 | A |
| $I_D$ @ $T_C$ = 100°C | Continuous Drain Current, $V_{GS}$ @ -10V | -16 | |
| $I_{DM}$ | Pulsed Drain Current ① | -76 | |
| $P_D$ @$T_C$ = 25°C | Power Dissipation | 140 | W |
| | Linear Derating Factor | 0.91 | W/°C |
| $V_{GS}$ | Gate-to-Source Voltage | ± 20 | V |
| $E_{AS}$ | Single Pulse Avalanche Energy② | 430 | mJ |
| $I_{AR}$ | Avalanche Current① | -11 | A |
| $E_{AR}$ | Repetitive Avalanche Energy① | 14 | mJ |
| dv/dt | Peak Diode Recovery dv/dt ③ | -5.0 | V/ns |
| $T_J$<br>$T_{STG}$ | Operating Junction and<br>Storage Temperature Range | -55 to + 175 | °C |
| | Soldering Temperature, for 10 seconds | 300 (1.6mm from case ) | |
| | Mounting torque, 6-32 or M3 srew | 10 lbf•in (1.1N•m) | |

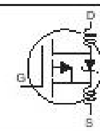
## Thermal Resistance

| | Parameter | Typ. | Max. | Units |
|---|---|---|---|---|
| $R_{\theta JC}$ | Junction-to-Case | —— | 1.1 | °C/W |
| $R_{\theta CS}$ | Case-to-Sink, Flat, Greased Surface | 0.50 | —— | |
| $R_{\theta JA}$ | Junction-to-Ambient | —— | 62 | |

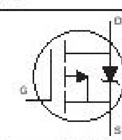
5/13/98

# IRF9540N

## Electrical Characteristics @ $T_J$ = 25°C (unless otherwise specified)

| | Parameter | Min. | Typ. | Max. | Units | Conditions |
|---|---|---|---|---|---|---|
| $V_{(BR)DSS}$ | Drain-to-Source Breakdown Voltage | -100 | — | — | V | $V_{GS}$ = 0V, $I_D$ = -250μA |
| $\Delta V_{(BR)DSS}/\Delta T_J$ | Breakdown Voltage Temp. Coefficient | — | -0.11 | — | V/°C | Reference to 25°C, $I_D$ = -1mA |
| $R_{DS(on)}$ | Static Drain-to-Source On-Resistance | — | — | 0.117 | Ω | $V_{GS}$ = -10V, $I_D$ = -11A ④ |
| $V_{GS(th)}$ | Gate Threshold Voltage | -2.0 | — | -4.0 | V | $V_{DS}$ = $V_{GS}$, $I_D$ = -250μA |
| $g_{fs}$ | Forward Transconductance | 5.3 | — | — | S | $V_{DS}$ = -50V, $I_D$ = -11A |
| $I_{DSS}$ | Drain-to-Source Leakage Current | — | — | -25 | μA | $V_{DS}$ = -100V, $V_{GS}$ = 0V |
| | | — | — | -250 | | $V_{DS}$ = -80V, $V_{GS}$ = 0V, $T_J$ = 150°C |
| $I_{GSS}$ | Gate-to-Source Forward Leakage | — | — | 100 | nA | $V_{GS}$ = 20V |
| | Gate-to-Source Reverse Leakage | — | — | -100 | | $V_{GS}$ = -20V |
| $Q_g$ | Total Gate Charge | — | — | 97 | nC | $I_D$ = -11A |
| $Q_{gs}$ | Gate-to-Source Charge | — | — | 15 | | $V_{DS}$ = -80V |
| $Q_{gd}$ | Gate-to-Drain ("Miller") Charge | — | — | 51 | | $V_{GS}$ = -10V, See Fig. 6 and 13 ④ |
| $t_{d(on)}$ | Turn-On Delay Time | — | 15 | — | ns | $V_{DD}$ = -50V |
| $t_r$ | Rise Time | — | 67 | — | | $I_D$ = -11A |
| $t_{d(off)}$ | Turn-Off Delay Time | — | 51 | — | | $R_G$ = 5.1Ω |
| $t_f$ | Fall Time | — | 51 | — | | $R_D$ = 4.2Ω, See Fig. 10 ④ |
| $L_D$ | Internal Drain Inductance | — | 4.5 | — | nH | Between lead, 6mm (0.25in.) from package and center of die contact  |
| $L_S$ | Internal Source Inductance | — | 7.5 | — | | |
| $C_{iss}$ | Input Capacitance | — | 1300 | — | pF | $V_{GS}$ = 0V |
| $C_{oss}$ | Output Capacitance | — | 400 | — | | $V_{DS}$ = -25V |
| $C_{rss}$ | Reverse Transfer Capacitance | — | 240 | — | | $f$ = 1.0MHz, See Fig. 5 |

## Source-Drain Ratings and Characteristics

| | Parameter | Min. | Typ. | Max. | Units | Conditions |
|---|---|---|---|---|---|---|
| $I_S$ | Continuous Source Current (Body Diode) | — | — | -23 | A | MOSFET symbol showing the integral reverse p-n junction diode.  |
| $I_{SM}$ | Pulsed Source Current (Body Diode) ① | — | — | -76 | | |
| $V_{SD}$ | Diode Forward Voltage | — | — | -1.6 | V | $T_J$ = 25°C, $I_S$ = -11A, $V_{GS}$ = 0V ④ |
| $t_{rr}$ | Reverse Recovery Time | — | 150 | 220 | ns | $T_J$ = 25°C, $I_F$ = -11A |
| $Q_{rr}$ | Reverse RecoveryCharge | — | 830 | 1200 | nC | di/dt = -100A/μs ④ |
| $t_{on}$ | Forward Turn-On Time | Intrinsic turn-on time is negligible (turn-on is dominated by $L_S$+$L_D$) | | | | |

**Notes:**

① Repetitive rating; pulse width limited by max. junction temperature. ( See fig. 11 )

② Starting $T_J$ = 25°C, L = 7.1mH $R_G$ = 25Ω, $I_{AS}$ = -11A. (See Figure 12)

③ $I_{SD} \leq$ -11A, di/dt $\leq$ -470A/μs, $V_{DD} \leq V_{(BR)DSS}$, $T_J \leq$ 175°C

④ Pulse width $\leq$ 300μs; duty cycle $\leq$ 2%.

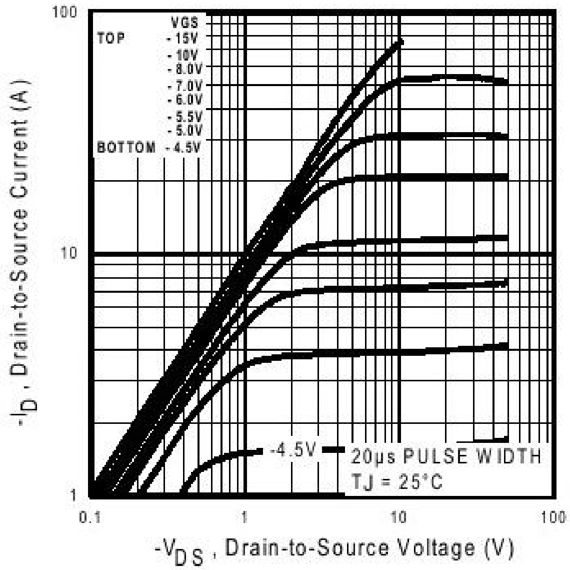



**Fig 1.** Typical Output Characteristics

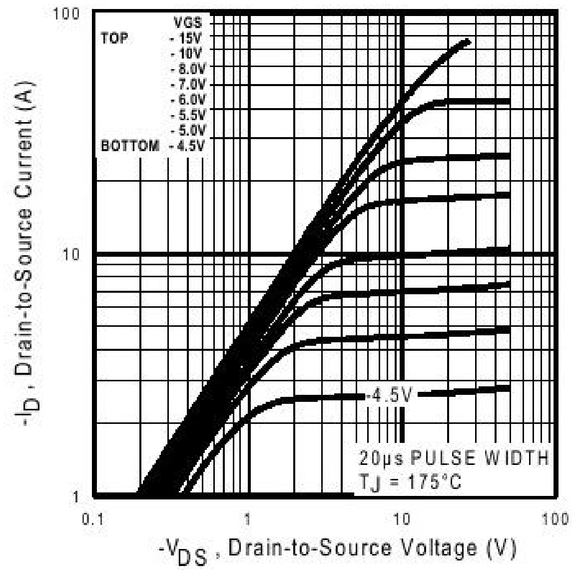



**Fig 2.** Typical Output Characteristics

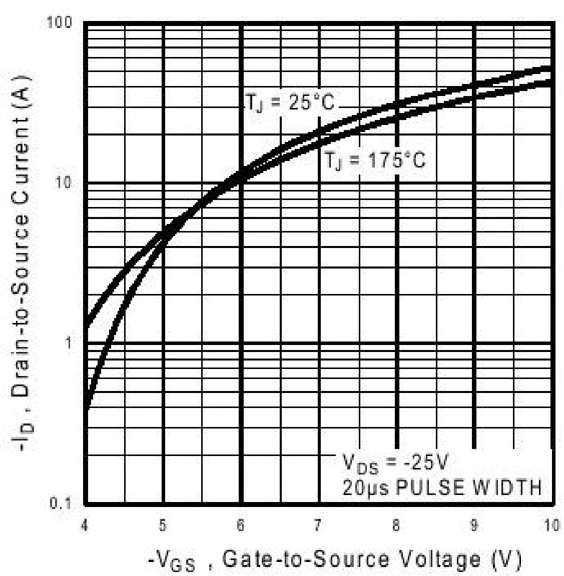



**Fig 3.** Typical Transfer Characteristics

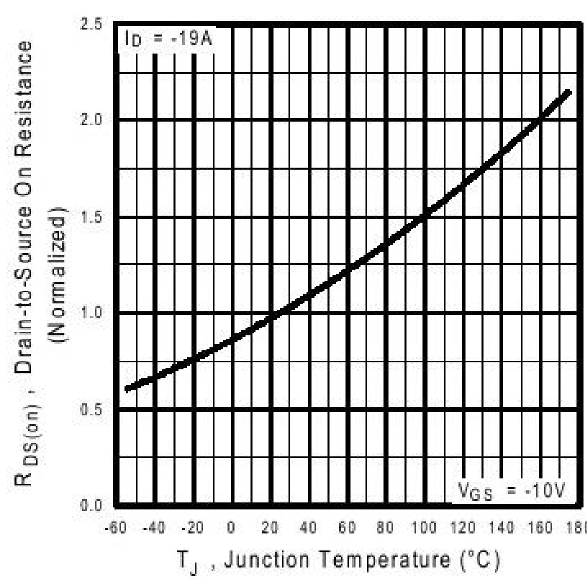



**Fig 4.** Normalized On-Resistance Vs. Temperature

# IRF9540N

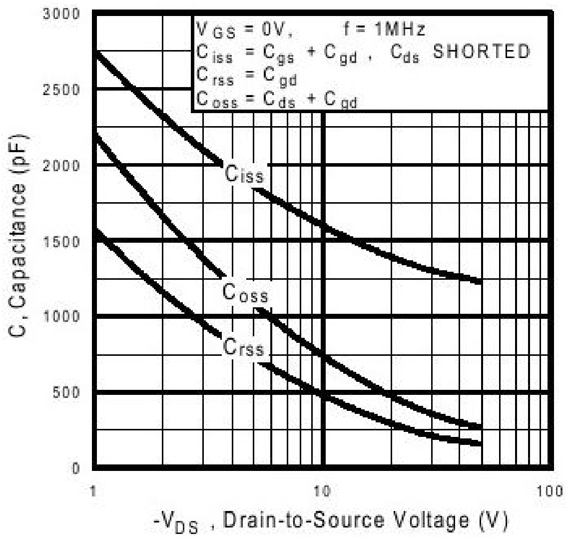



**Fig 5.** Typical Capacitance Vs. Drain-to-Source Voltage

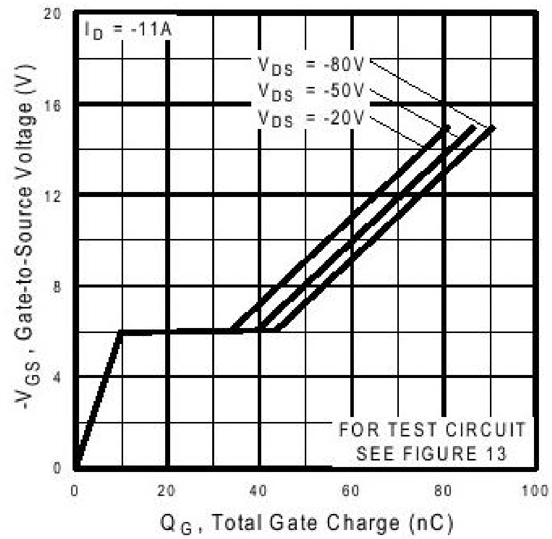



**Fig 6.** Typical Gate Charge Vs. Gate-to-Source Voltage

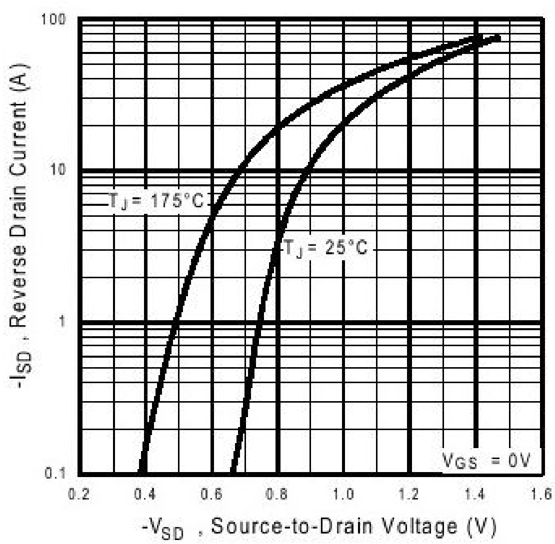



**Fig 7.** Typical Source-Drain Diode Forward Voltage

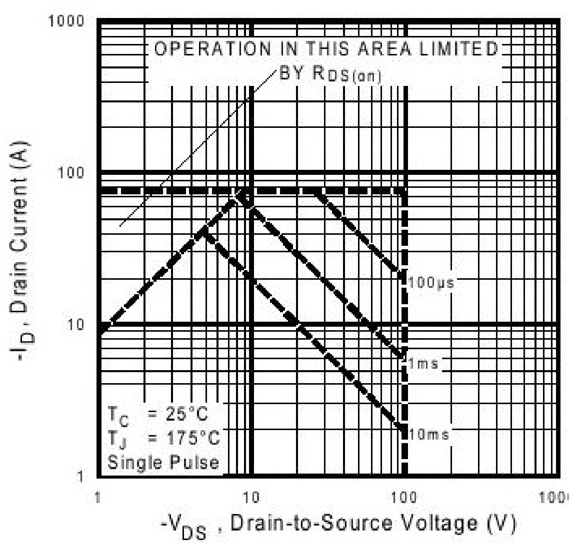



**Fig 8.** Maximum Safe Operating Area

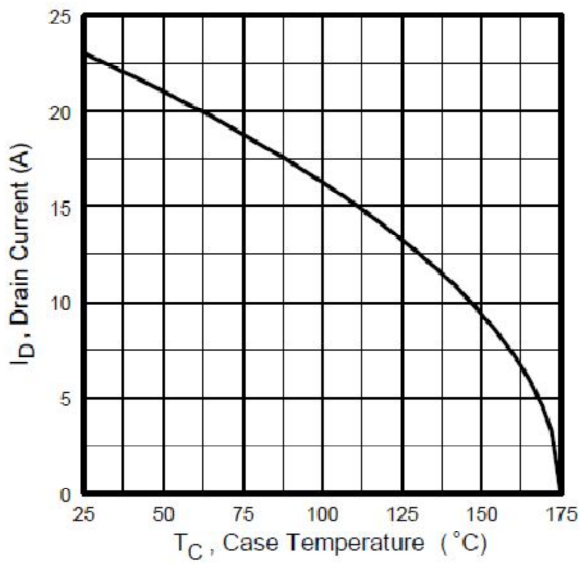



Fig 9. Maximum Drain Current Vs. Case Temperature

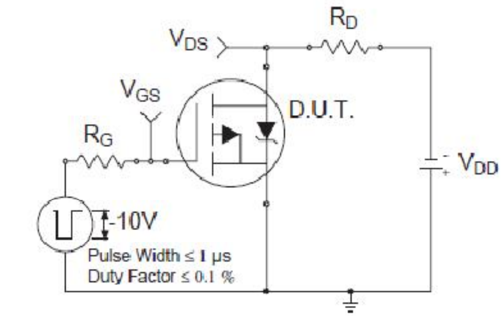



Fig 10a. Switching Time Test Circuit

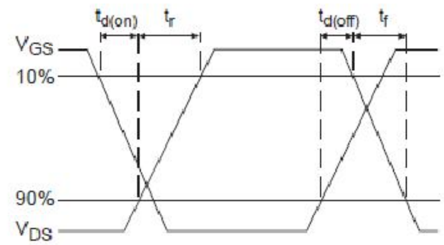



Fig 10b. Switching Time Waveforms

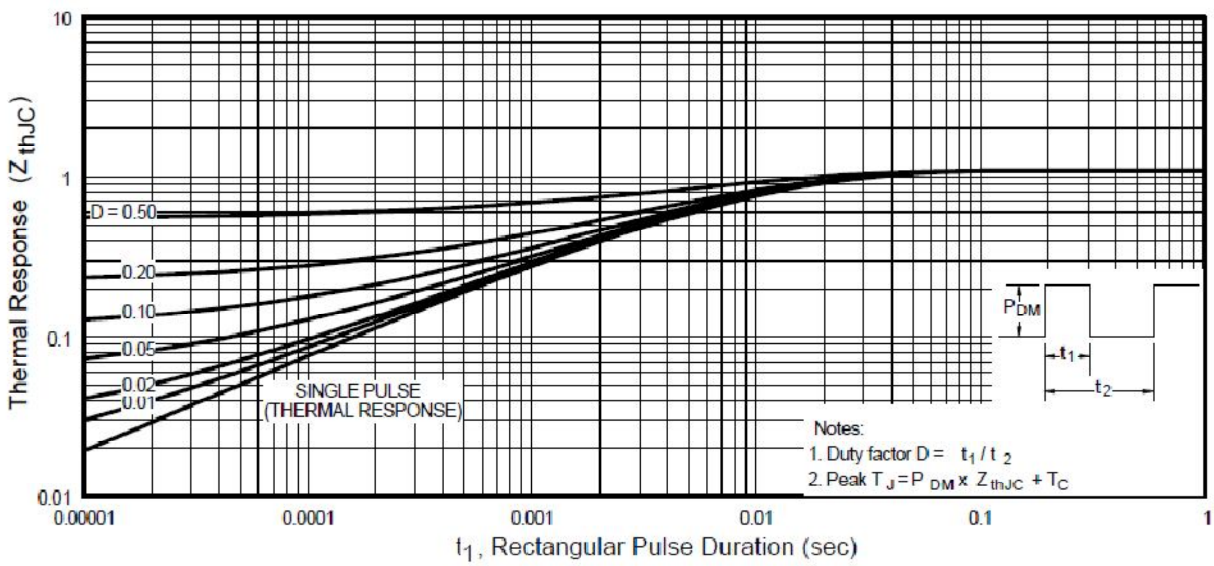



Fig 11. Maximum Effective Transient Thermal Impedance, Junction-to-Case

# IRF9540N

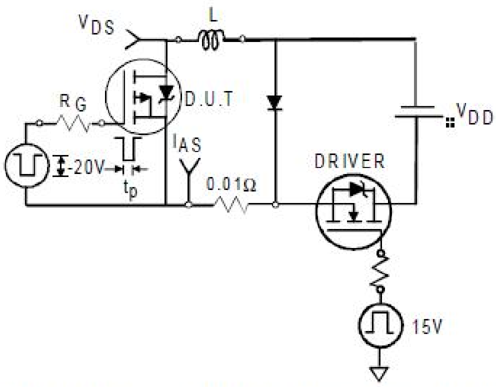



**Fig 12a.** Unclamped Inductive Test Circuit

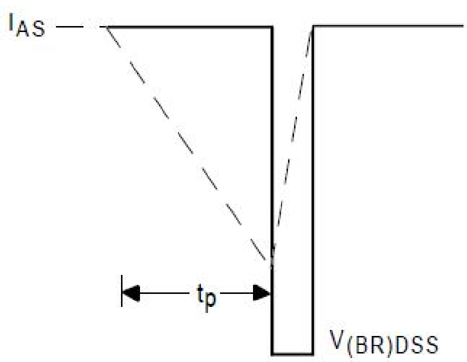



**Fig 12b.** Unclamped Inductive Waveforms

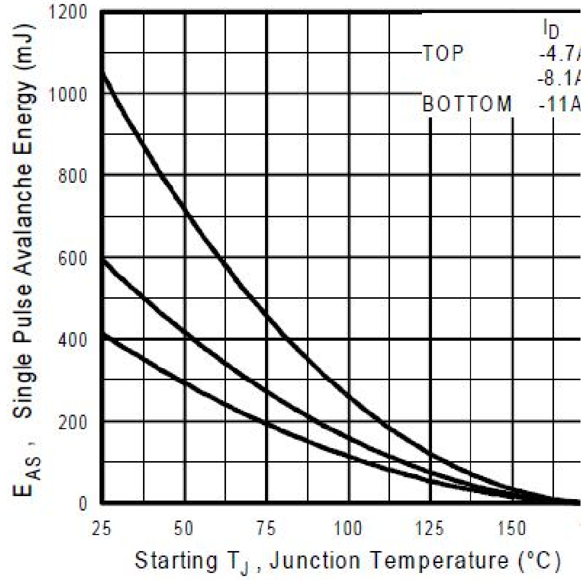



**Fig 12c.** Maximum Avalanche Energy Vs. Drain Current

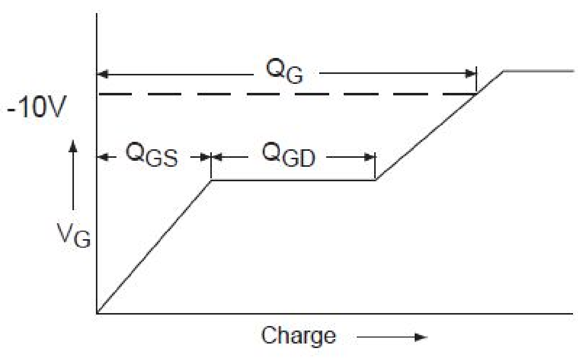



**Fig 13a.** Basic Gate Charge Waveform

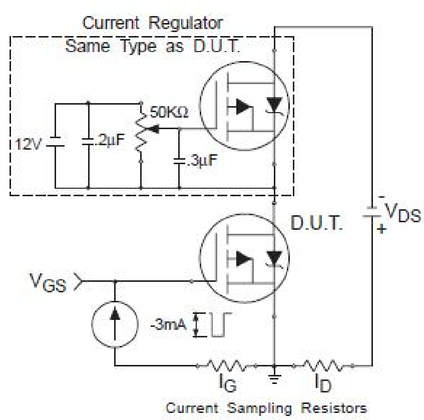
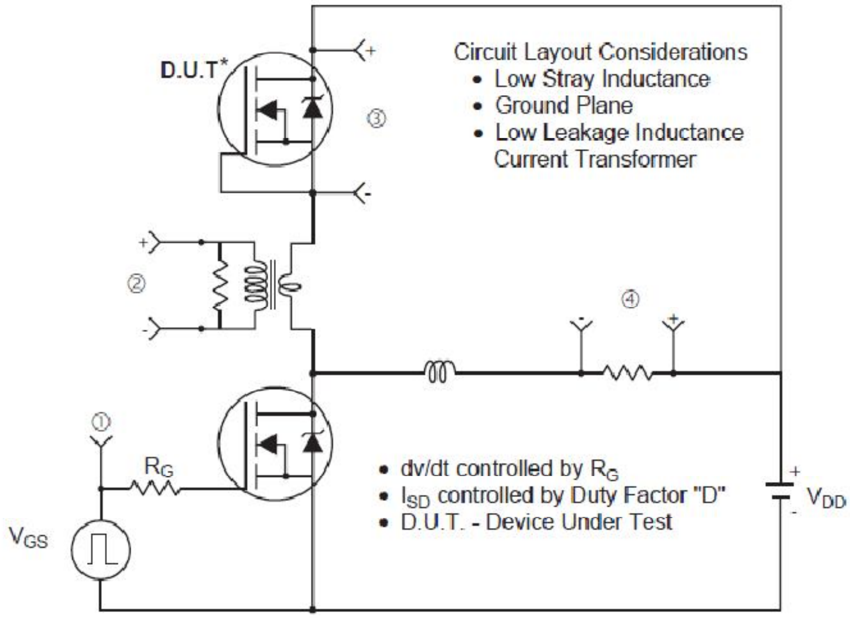


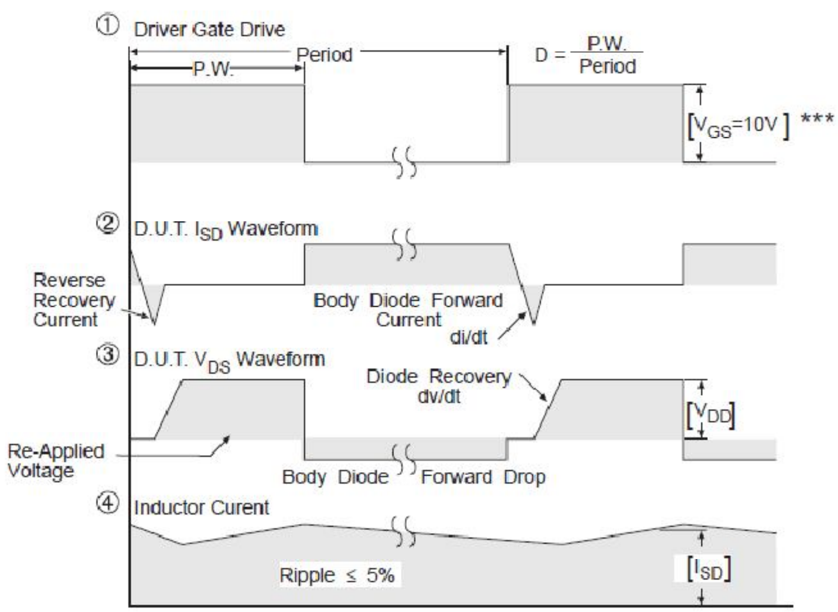

**Fig 13b.** Gate Charge Test Circuit

IOR **IRF9540N**

## Peak Diode Recovery dv/dt Test Circuit




* Reverse Polarity of D.U.T for P-Channel




*** $V_{GS}$ = 5.0V for Logic Level and 3V Drive Devices

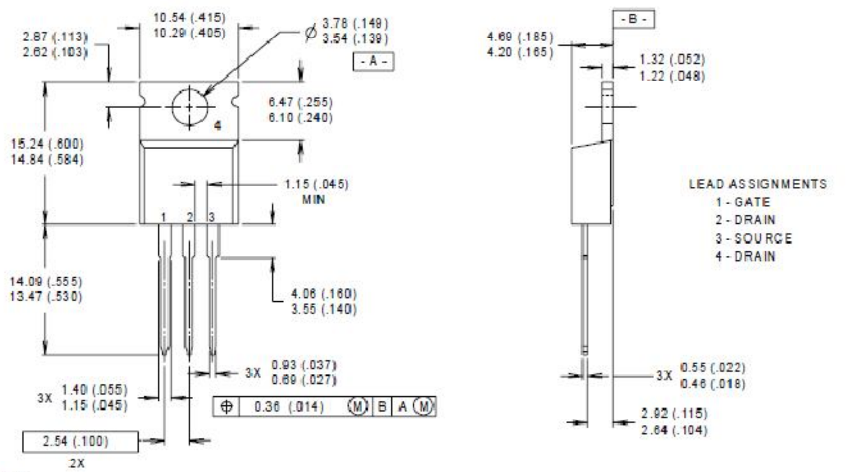
**Fig 14.** For P-Channel HEXFETS

# IRF9540N

## Package Outline

**TO-220AB Outline**

Dimensions are shown in millimeters (inches)




NOTES:

1 DIMENSIONING & TOLERANCING PER ANSI Y14.5M, 1982.

2 CONTROLLING DIMENSION : INCH

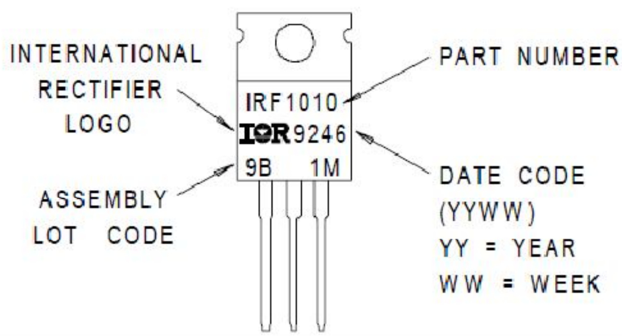
3 OUTLINE CONFORMS TO JEDEC OUTLINE TO-220AB.

4 HEATSINK & LEAD MEASUREMENTS DO NOT INCLUDE BURRS.

## Part Marking Information

**TO-220AB**

EXAMPLE : THIS IS AN IRF1010
WITH ASSEMBLY
LOT CODE 9B1M




International
IOR Rectifier

**WORLD HEADQUARTERS:** 233 Kansas St., El Segundo, California 90245, Tel: (310) 322 3331
**EUROPEAN HEADQUARTERS:** Hurst Green, Oxted, Surrey RH8 9BB, UK Tel: ++ 44 1883 732020
**IR CANADA:** 7321 Victoria Park Ave., Suite 201, Markham, Ontario L3R 2Z8, Tel: (905) 475 1897
**IR GERMANY:** Saalburgstrasse 157, 61350 Bad Homburg Tel: ++ 49 6172 96590
**IR ITALY:** Via Liguria 49, 10071 Borgaro, Torino Tel: ++ 39 11 451 0111
**IR FAR EAST:** K&H Bldg., 2F, 30-4 Nishi-Ikebukuro 3-Chome, Toshima-Ku, Tokyo Japan 171 Tel: 81 3 3983 0086
**IR SOUTHEAST ASIA:** 315 Outram Road, #10-02 Tan Boon Liat Building, Singapore 0316 Tel: 65 221 8371

*http://www.irf.com/ Data and specifications subject to change without notice. 5/98*

# N-Channel MOSFET IRF540

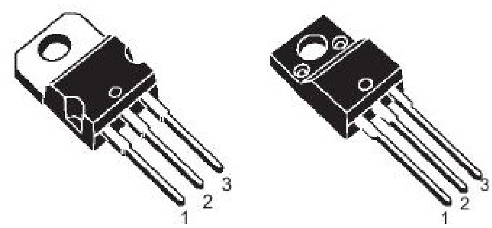
SGS-THOMSON MICROELECTRONICS

# IRF540
# IRF540FI

## N - CHANNEL100V - 00.50Ω - 30A - TO-220/TO-220FI POWER MOSFET

| TYPE | $V_{DSS}$ | $R_{DS(on)}$ | $I_D$ |
|---|---|---|---|
| IRF540 | 100 V | < 0.077 Ω | 30 A |
| IRF540FI | 100 V | < 0.077 Ω | 16 A |

- TYPICAL $R_{DS(on)}$ = 0.050 Ω
- AVALANCHE RUGGED TECHNOLOGY
- 100% AVALANCHE TESTED
- REPETITIVE AVALANCHE DATA AT 100°C
- LOW GATE CHARGE
- HIGH CURRENT CAPABILITY
- 175°C OPERATING TEMPERATURE
- APPLICATION ORIENTED CHARACTERIZATION

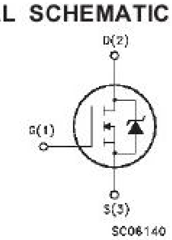



TO-220 TO-220FI

### APPLICATIONS

- HIGH CURRENT, HIGH SPEED SWITCHING
- SOLENOID AND RELAY DRIVERS
- DC-DC & DC-AC CONVERTER
- AUTOMOTIVE ENVIRONMENT (INJECTION, ABS, AIR-BAG, LAMP DRIVERS Etc.)

INTERNAL SCHEMATIC DIAGRAM




### ABSOLUTE MAXIMUM RATINGS

| Symbol | Parameter | Value | | Unit |
|---|---|---|---|---|
| | | IRF530 | IRF530FI | |
| $V_{DS}$ | Drain-source Voltage ($V_{GS}$ = 0) | 100 | | V |
| $V_{DGR}$ | Drain- gate Voltage ($R_{GS}$ = 20 kΩ) | 100 | | V |
| $V_{GS}$ | Gate-source Voltage | ± 20 | | V |
| $I_D$ | Drain Current (continuous) at $T_c$ = 25 °C | 30 | 17 | A |
| $I_D$ | Drain Current (continuous) at $T_c$ = 100 °C | 21 | 12 | A |
| $I_{DM}(\bullet)$ | Drain Current (pulsed) | 120 | 120 | A |
| $P_{tot}$ | Total Dissipation at $T_c$ = 25 °C | 150 | 45 | W |
| | Derating Factor | 1 | 0.3 | W/°C |
| Viso | Insulation Withstand Voltage (DC) | - | 2000 | V |
| $T_{stg}$ | Storage Temperature | -65 to 175 | | °C |
| $T_j$ | Max. Operating Junction Temperature | 175 | | °C |

(•) Pulse width limited by safe operating area (1) $I_{SD} \leq 30$ A, di/dt ≤ 200 A/µs, $V_{DD} \leq V_{(BR)DSS}$, $T_j \leq T_{JMAX}$

## THERMAL DATA

| | | | TO-220 | TO220-FI | |
|---|---|---|---|---|---|
| $R_{thj-case}$ | Thermal Resistance Junction-case | Max | 1 | 3.33 | °C/W |
| $R_{thj-amb}$ | Thermal Resistance Junction-ambient | Max | 62.5 | | °C/W |
| $R_{thc-sink}$ | Thermal Resistance Case-sink | Typ | 0.5 | | °C/W |
| $T_l$ | Maximum Lead Temperature For Soldering Purpose | | 300 | | °C |

## AVALANCHE CHARACTERISTICS

| Symbol | Parameter | Max Value | Unit |
|---|---|---|---|
| $I_{AR}$ | Avalanche Current, Repetitive or Not-Repetitive (pulse width limited by $T_j$ max | 30 | A |
| $E_{AS}$ | Single Pulse Avalanche Energy (starting $T_j$ = 25 °C, $I_D = I_{AR}$, $V_{DD}$ = 25 V) | 200 | mJ |

## ELECTRICAL CHARACTERISTICS ($T_{case}$ = 25 °C unless otherwise specified)

OFF

| Symbol | Parameter | Test Conditions | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|
| $V_{(BR)DSS}$ | Drain-source Breakdown Voltage | $I_D$ = 250 μA $V_{GS}$ = 0 | 100 | | | V |
| $I_{DSS}$ | Zero Gate Voltage Drain Current ($V_{GS}$ = 0) | $V_{DS}$ = Max Rating<br>$V_{DS}$ = Max Rating $T_c$ = 125 °C | | | 1<br>10 | μA<br>μA |
| $I_{GSS}$ | Gate-body Leakage Current ($V_{DS}$ = 0) | $V_{GS}$ = ± 20 V | | | ± 100 | nA |

ON (□)

| Symbol | Parameter | Test Conditions | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|
| $V_{GS(th)}$ | Gate Threshold Voltage | $V_{DS} = V_{GS}$ $I_D$ = 250 μA | 2 | 3 | 4 | V |
| $R_{DS(on)}$ | Static Drain-source On Resistance | $V_{GS}$ = 10V $I_D$ = 15 A | | 0.05 | 0.077 | Ω |
| $I_{D(on)}$ | On State Drain Current | $V_{DS} > I_{D(on)} \times R_{DS(on)max}$<br>$V_{GS}$ = 10 V | 30 | | | A |

DYNAMIC

| Symbol | Parameter | Test Conditions | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|
| $g_{fs}$ (□) | Forward Transconductance | $V_{DS} > I_{D(on)} \times R_{DS(on)max}$ $I_D$ = 15 A | 10 | 20 | | S |
| $C_{iss}$<br>$C_{oss}$<br>$C_{rss}$ | Input Capacitance<br>Output Capacitance<br>Reverse Transfer Capacitance | $V_{DS}$ = 25 V f = 1 MHz $V_{GS}$ = 0 | | 2600<br>350<br>85 | 3600<br>500<br>120 | pF<br>pF<br>pF |

**ELECTRICAL CHARACTERISTICS** (continued)

SWITCHING ON

| Symbol | Parameter | Test Conditions | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|
| $t_{d(on)}$<br>$t_r$ | Turn-on Time<br>Rise Time | $V_{DD}$ = 50 V  $I_D$ = 15 A<br>$R_G$ = 4.7 Ω  $V_{GS}$ = 10 V | | 20<br>60 | 28<br>85 | ns<br>ns |
| $Q_g$<br>$Q_{gs}$<br>$Q_{gd}$ | Total Gate Charge<br>Gate-Source Charge<br>Gate-Drain Charge | $V_{DD}$ =80 V  $I_D$ =30 A  $V_{GS}$ = 10 V | | 80<br>13<br>28 | 110 | nC<br>nC<br>nC |

SWITCHING OFF

| Symbol | Parameter | Test Conditions | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|
| $t_{r(Voff)}$<br>$t_f$<br>$t_c$ | Off-voltage Rise Time<br>Fall Time<br>Cross-over Time | $V_{DD}$ = 80 V  $I_D$ =30 A<br>$R_G$ = 4.7 Ω  $V_{GS}$ = 10 V | | 22<br>25<br>55 | 30<br>35<br>75 | ns<br>ns<br>ns |

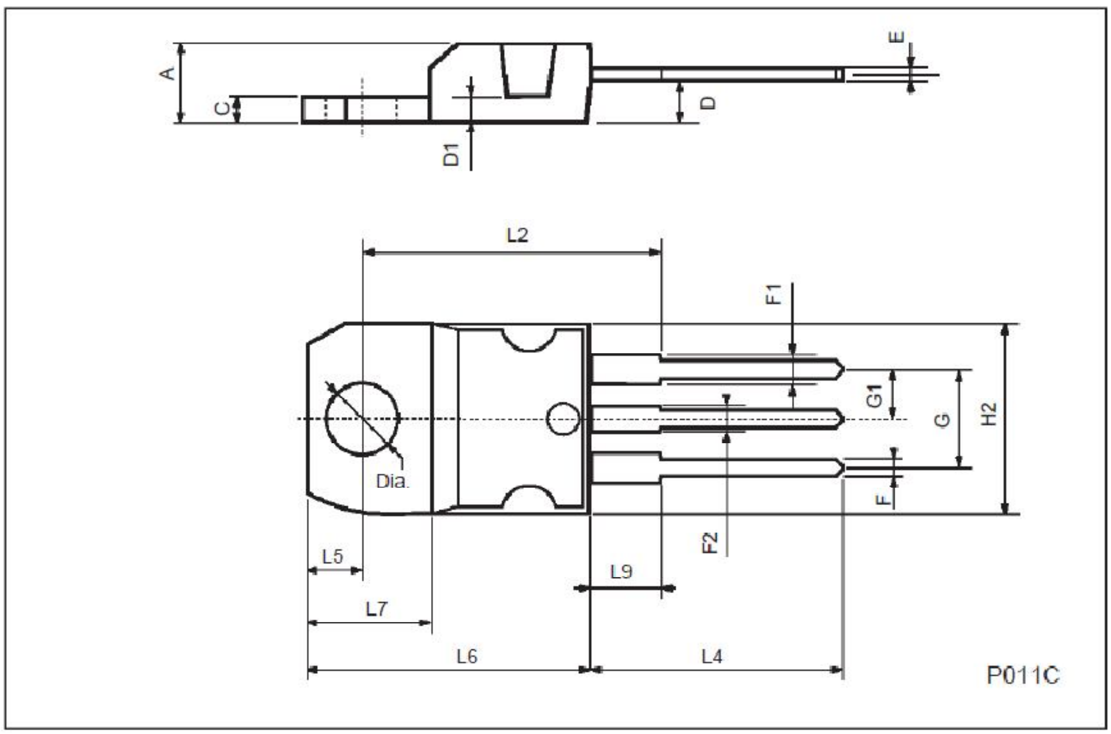
SOURCE DRAIN DIODE

| Symbol | Parameter | Test Conditions | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|
| $I_{SD}$<br>$I_{SDM}$(•) | Source-drain Current<br>Source-drain Current (pulsed) | | | | 30<br>120 | A<br>A |
| $V_{SD}$ (□) | Forward On Voltage | $I_{SD}$ = 50 A  $V_{GS}$ = 0 | | | 1.5 | V |
| $t_{rr}$<br>$Q_{rr}$<br>$I_{RRM}$ | Reverse Recovery Time<br>Reverse Recovery Charge<br>Reverse Recovery Current | $I_{SD}$ =30 A  di/dt = 100 A/μs<br>$V_{DD}$ = 30 V  $T_j$ = 150 °C | | 175<br>1.1<br>12.5 | | ns<br>μC<br>A |

(□) Pulsed: Pulse duration = 300 μs, duty cycle 1.5 %
(•) Pulse width limited by safe operating area

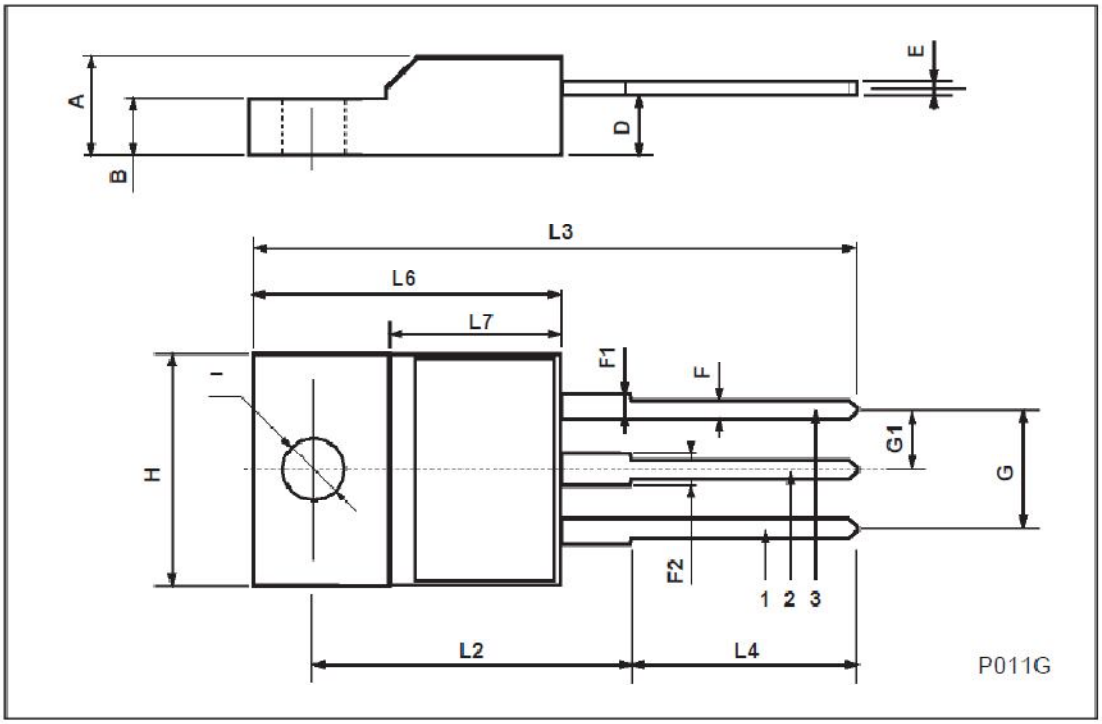
## TO-220 MECHANICAL DATA

| DIM. | mm | | | inch | | |
|---|---|---|---|---|---|---|
| | MIN. | TYP. | MAX. | MIN. | TYP. | MAX. |
| A | 4.40 | | 4.60 | 0.173 | | 0.181 |
| C | 1.23 | | 1.32 | 0.048 | | 0.051 |
| D | 2.40 | | 2.72 | 0.094 | | 0.107 |
| D1 | | 1.27 | | | 0.050 | |
| E | 0.49 | | 0.70 | 0.019 | | 0.027 |
| F | 0.61 | | 0.88 | 0.024 | | 0.034 |
| F1 | 1.14 | | 1.70 | 0.044 | | 0.067 |
| F2 | 1.14 | | 1.70 | 0.044 | | 0.067 |
| G | 4.95 | | 5.15 | 0.194 | | 0.203 |
| G1 | 2.4 | | 2.7 | 0.094 | | 0.106 |
| H2 | 10.0 | | 10.40 | 0.393 | | 0.409 |
| L2 | | 16.4 | | | 0.645 | |
| L4 | 13.0 | | 14.0 | 0.511 | | 0.551 |
| L5 | 2.65 | | 2.95 | 0.104 | | 0.116 |
| L6 | 15.25 | | 15.75 | 0.600 | | 0.620 |
| L7 | 6.2 | | 6.6 | 0.244 | | 0.260 |
| L9 | 3.5 | | 3.93 | 0.137 | | 0.154 |
| DIA. | 3.75 | | 3.85 | 0.147 | | 0.151 |



## ISOWATT220 MECHANICAL DATA

| DIM. | mm | | | inch | | |
|---|---|---|---|---|---|---|
| | MIN. | TYP. | MAX. | MIN. | TYP. | MAX. |
| A | 4.4 | | 4.6 | 0.173 | | 0.181 |
| B | 2.5 | | 2.7 | 0.098 | | 0.106 |
| D | 2.5 | | 2.75 | 0.098 | | 0.108 |
| E | 0.4 | | 0.7 | 0.015 | | 0.027 |
| F | 0.75 | | 1 | 0.030 | | 0.039 |
| F1 | 1.15 | | 1.7 | 0.045 | | 0.067 |
| F2 | 1.15 | | 1.7 | 0.045 | | 0.067 |
| G | 4.95 | | 5.2 | 0.195 | | 0.204 |
| G1 | 2.4 | | 2.7 | 0.094 | | 0.106 |
| H | 10 | | 10.4 | 0.393 | | 0.409 |
| L2 | | 16 | | | 0.630 | |
| L3 | 28.6 | | 30.6 | 1.126 | | 1.204 |
| L4 | 9.8 | | 10.6 | 0.385 | | 0.417 |
| L6 | 15.9 | | 16.4 | 0.626 | | 0.645 |
| L7 | 9 | | 9.3 | 0.354 | | 0.366 |
| Ø | 3 | | 3.2 | 0.118 | | 0.126 |



# Transistor

# NPN

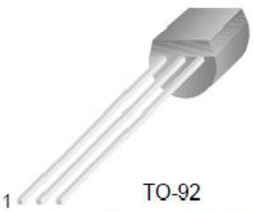
# 2N2222

FAIRCHILD SEMICONDUCTOR®



# PN2222

## General Purpose Transistor



1

TO-92

1. Emitter 2. Base 3. Collector

## NPN Epitaxial Silicon Transistor

### Absolute Maximum Ratings $T_a$=25°C unless otherwise noted

| Symbol | Parameter | Value | Units |
|---|---|---|---|
| $V_{CBO}$ | Collector-Base Voltage | 60 | V |
| $V_{CEO}$ | Collector-Emitter Voltage | 30 | V |
| $V_{EBO}$ | Emitter-Base Voltage | 5 | V |
| $I_C$ | Collector Current | 600 | mA |
| $P_C$ | Collector Power Dissipation | 625 | mW |
| $T_J$ | Junction Temperature | 150 | °C |
| $T_{STG}$ | Storage Temperature | -55 ~ 150 | °C |

### Electrical Characteristics $T_a$=25°C unless otherwise noted

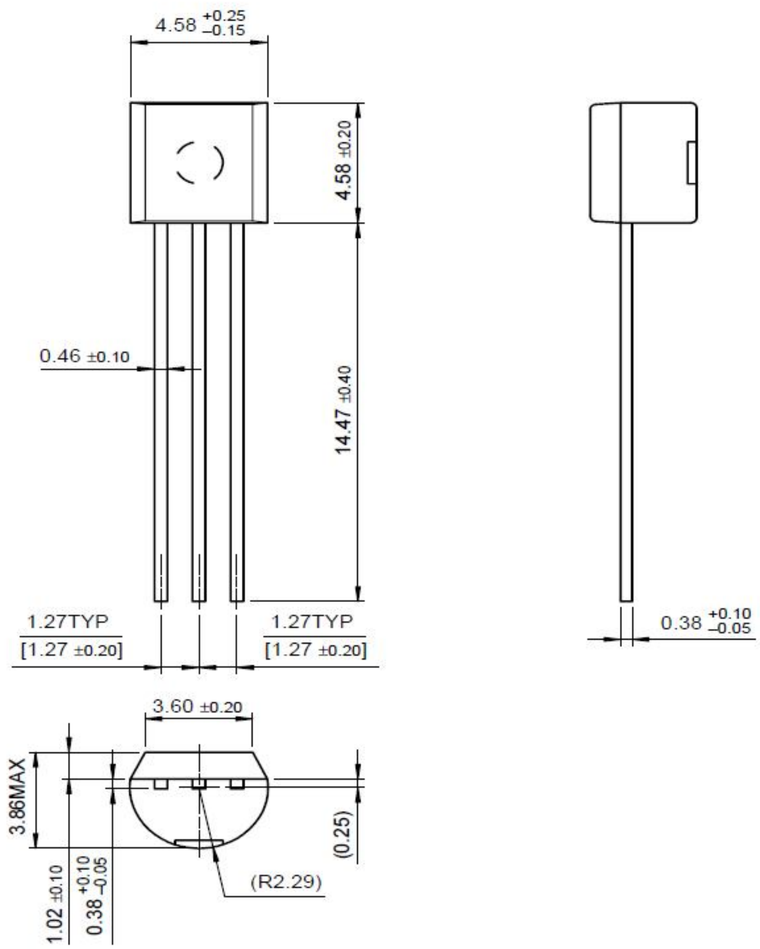
| Symbol | Parameter | Test Condition | Min. | Max. | Units |
|---|---|---|---|---|---|
| $BV_{CBO}$ | Collector-Base Breakdown Voltage | $I_C$=10μA, $I_E$=0 | 60 | | V |
| $BV_{CEO}$ | Collector Emitter Breakdown Voltage | $I_C$=10mA, $I_B$=0 | 30 | | V |
| $BV_{EBO}$ | Emitter-Base Breakdown Voltage | $I_E$=10μA, $I_C$=0 | 5 | | V |
| $I_{CBO}$ | Collector Cut-off Current | $V_{CB}$=50V, $I_E$=0 | | 0.01 | μA |
| $I_{EBO}$ | Emitter Cut-off Current | $V_{EB}$=3V, $I_C$=0 | | 10 | nA |
| $h_{FE}$ | DC Current Gain | $V_{CE}$=10V, $I_C$=0.1mA<br>$V_{CE}$=10V, *$I_C$=150mA | 35<br>100 | <br>300 | |
| $V_{CE}$ (sat) | * Collector-Emitter Saturation Voltage | $I_C$=500mA, $I_B$=50mA | | 1 | V |
| $V_{BE}$ (sat) | * Base-Emitter Saturation Voltage | $I_C$=500mA, $I_B$=50mA | | 2 | V |
| $f_T$ | Current Gain Bandwidth Product | $V_{CE}$=20V, $I_C$=20mA, f=100MHz | 300 | | MHz |
| $C_{ob}$ | Output Capacitance | $V_{CB}$=10V, $I_E$=0, f=1MHz | | 8 | pF |

* Pulse Test: Pulse Width≤300μs, Duty Cycle≤2%

## Package Dimensions

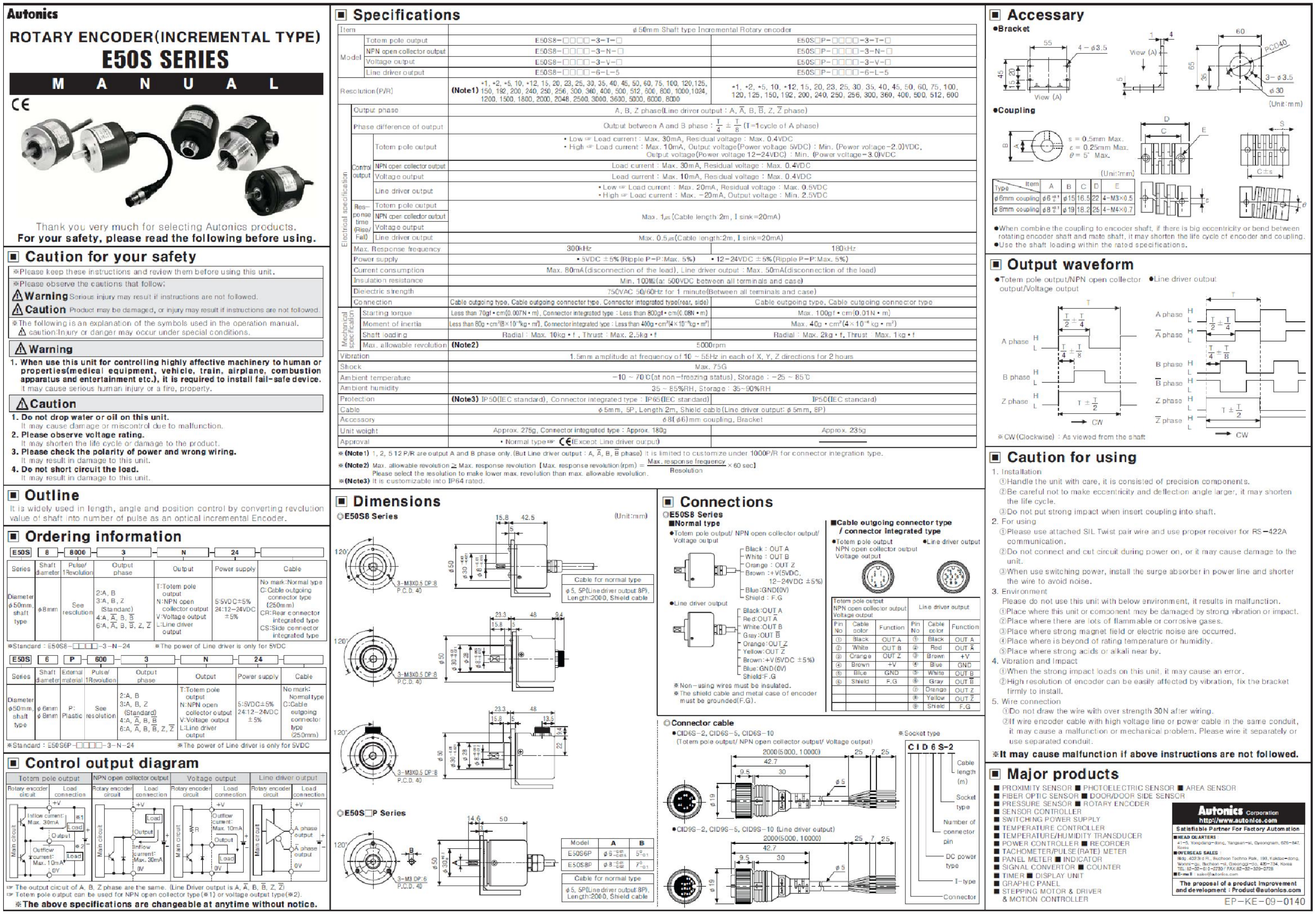
PN2222

TO-92




Dimensions in Millimeters

# INCREMNTAL ENCODER



Autonics

# ROTARY ENCODER(INCREMENTAL TYPE)
# E50S SERIES
M A N U A L

Thank you very much for selecting Autonics products.
**For your safety, please read the following before using.**

## Caution for your safety

※Please keep these instructions and review them before using this unit.
※Please observe the cautions that follow;
⚠Warning Serious injury may result if instructions are not followed.
⚠Caution Product may be damaged, or injury may result if instructions are not followed.
※The following is an explanation of the symbols used in the operation manual.
⚠ caution:Injury or danger may occur under special conditions.

### ⚠Warning

1. **When use this unit for controlling highly affective machinery to human or properties(medical equipment, vehicle, train, airplane, combustion apparatus and entertainment etc.), it is required to install fail-safe device.** It may cause serious human injury or a fire, property.

### ⚠Caution

1. **Do not drop water or oil on this unit.** It may cause damage or miscontrol due to malfunction.
2. **Please observe voltage rating.** It may shorten the life cycle or damage to the product.
3. **Please check the polarity of power and wrong wiring.** It may result in damage to this unit.
4. **Do not short circuit the load.** It may result in damage to this unit.

## Outline

It is widely used in length, angle and position control by converting revolution value of shaft into number of pulse as an optical incremental Encoder.

## Ordering information

E50S 8 - 8000 - 3 - N - 24

| Series | Shaft diameter | Pulse/ 1Revolution | Output phase | Output | Power supply | Cable |
|---|---|---|---|---|---|---|
| Diameter φ50mm, shaft type | φ8mm | See resolution | 2:A, B 3:A, B, Z (Standard) 4:A, $\overline{A}$, B, $\overline{B}$ 6:A, $\overline{A}$, B, $\overline{B}$, Z, $\overline{Z}$ | T:Totem pole output N:NPN open collector output V:Voltage output L:Line driver output | 5:5VDC±5% 24:12–24VDC ±5% | No mark:Normal type C:Cable outgoing connector type (250mm) CR:Rear connector integrated type CS:Side connector integrated type |

※Standard : E50S8-□□□□-3-N-24 ※The power of Line driver is only for 5VDC

E50S 6 P - 600 - 3 - N - 24

| Series | Shaft diameter | External material | Pulse/ 1Revolution | Output phase | Output | Power supply | Cable |
|---|---|---|---|---|---|---|---|
| Diameter φ50mm, shaft type | φ6mm φ8mm | P: Plastic | See resolution | 2:A, B 3:A, B, Z (Standard) 4:A, $\overline{A}$, B, $\overline{B}$ 6:A, $\overline{A}$, B, $\overline{B}$, Z, $\overline{Z}$ | T:Totem pole output N:NPN open collector output V:Voltage output L:Line driver output | 5:5VDC±5% 24:12–24VDC ±5% | No mark: Normal type C:Cable outgoing connector type (250mm) |

※Standard : E50S6P-□□□□-3-N-24 ※The power of Line driver is only for 5VDC

## Control output diagram

Totem pole output / NPN open collector output / Voltage output / Line driver output

☞ The output circuit of A, B, Z phase are the same. (Line Driver output is A, $\overline{A}$, B, $\overline{B}$, Z, $\overline{Z}$)
☞ Totem pole output can be used for NPN open collector type(※1) or voltage output type(※2).
**※The above specifications are changeable at anytime without notice.**

## Specifications

| Item | | φ50mm Shaft type Incremental Rotary encoder | |
|---|---|---|---|
| Model | Totem pole output | E50S8-□□□□-3-T-□ | E50S□P-□□□□-3-T-□ |
| | NPN open collector output | E50S8-□□□□-3-N-□ | E50S□P-□□□□-3-N-□ |
| | Voltage output | E50S8-□□□□-3-V-□ | E50S□P-□□□□-3-V-□ |
| | Line driver output | E50S8-□□□□-6-L-5 | E50S□P-□□□□-6-L-5 |
| Resolution(P/R) | (Note1) | *1, *2, *5, 10, *12, 15, 20, 23, 25, 30, 35, 40, 45, 50, 60, 75, 100, 120, 125, 150, 192, 200, 240, 250, 256, 300, 360, 400, 500, 512, 600, 800, 1000, 1024, 1200, 1500, 1800, 2000, 2048, 2500, 3000, 3600, 5000, 6000, 8000 | *1, *2, *5, 10, *12, 15, 20, 23, 25, 30, 35, 40, 45, 50, 60, 75, 100, 120, 125, 150, 192, 200, 240, 250, 256, 300, 360, 400, 500, 512, 600 |
| Output phase | | A, B, Z phase(Line driver output : A, $\overline{A}$, B, $\overline{B}$, Z, $\overline{Z}$ phase) | |
| Phase difference of output | | Output between A and B phase : $\frac{T}{4} \pm \frac{T}{8}$ (T=1cycle of A phase) | |
| Control output | Totem pole output | • Low ☞ Load current : Max. 30mA, Residual voltage : Max. 0.4VDC • High ☞ Load current : Max. 10mA, Output voltage(Power voltage 5VDC) : Min. (Power voltage-2.0)VDC, Output voltage(Power voltage 12–24VDC) : Min. (Power voltage-3.0)VDC | |
| | NPN open collector output | Load current : Max. 30mA, Residual voltage : Max. 0.4VDC | |
| | Voltage output | Load current : Max. 10mA, Residual voltage : Max. 0.4VDC | |
| | Line driver output | • Low ☞ Load current : Max. 20mA, Residual voltage : Max. 0.5VDC • High ☞ Load current : Max. −20mA, Output voltage : Min. 2.5VDC | |
| Response time (Rise/Fall) | Totem pole output / NPN open collector output / Voltage output | Max. 1μs (Cable length 2m, I sink=20mA) | |
| | Line driver output | Max. 0.5μs (Cable length:2m, I sink=20mA) | |
| Max. Response frequency | | 300kHz | 180kHz |
| Power supply | | • 5VDC ±5%(Ripple P-P:Max. 5%) • 12–24VDC ±5%(Ripple P-P:Max. 5%) | |
| Current consumption | | Max. 80mA(disconnection of the load), Line driver output : Max. 50mA(disconnection of the load) | |
| Insulation resistance | | Min. 100MΩ(at 500VDC between all terminals and case) | |
| Dielectric strength | | 750VAC 50/60Hz for 1 minute(Between all terminals and case) | |
| Connection | | Cable outgoing type, Cable outgoing connector type, Connector integrated type(rear, side) | Cable outgoing type, Cable outgoing connector type |
| Mechanical specification | Starting torque | Less than 70gf·cm(0.007N·m), Connector integrated type : Less than 80gf·cm(0.08N·m) | Max. 100gf·cm(0.01N·m) |
| | Moment of inertia | Less than 80g·cm²(8×10⁻⁶kg·m²), Connector integrated type : Less than 400g·cm²(4×10⁻⁵kg·m²) | Max. 40g·cm²(4×10⁻⁶ kg·m²) |
| | Shaft loading | Radial : Max. 10kg·f, Thrust : Max. 2.5kg·f | Radial : Max. 2kg·f, Thrust : Max. 1kg·f |
| | Max. allowable revolution (Note2) | 5000rpm | |
| Vibration | | 1.5mm amplitude at frequency of 10 ~ 55Hz in each of X, Y, Z directions for 2 hours | |
| Shock | | Max. 75G | |
| Ambient temperature | | −10 ~ 70℃(at non-freezing status), Storage : −25 ~ 85℃ | |
| Ambient humidity | | 35 ~ 85%RH, Storage : 35~90%RH | |
| Protection | | (Note3) IP50(IEC standard), Connector integrated type : IP65(IEC standard) | IP50(IEC standard) |
| Cable | | φ5mm, 5P, Length 2m, Shield cable(Line driver output: φ5mm, 8P) | |
| Accessory | | φ8(φ6)mm coupling, Bracket | |
| Unit weight | | Approx. 275g, Connector integrated type : Approx. 180g | Approx. 23.5g |
| Approval | | • Normal type ☞ CE(Except Line driver output) | |

※(Note1) 1, 2, 5 12 P/R are output A and B phase only.(But Line driver output : A, $\overline{A}$, B, $\overline{B}$ phase) It is limited to customize under 1000P/R for connector integration type.
※(Note2) Max. allowable revolution ≥ Max. response revolution [Max. response revolution(rpm) = $\frac{\text{Max. response frequency}}{\text{Resolution}} \times 60$ sec] Please select the resolution to make lower max. revolution than max. allowable revolution.
※(Note3) It is customizable into IP64 rated.

## Dimensions

○E50S8 Series (Unit:mm)

Cable for normal type φ5, 5P(Line driver output 8P), Length:2000, Shield cable

○E50S□P Series

| Model | A | B |
|---|---|---|
| E50S6P | φ6 | 5 |
| E50S8P | φ8 | 7 |

Cable for normal type φ5, 5P(Line driver output 8P), Length:2000, Shield cable

## Connections

○E50S8 Series
■Normal type
●Totem pole output/ NPN open collector output/ Voltage output
Black : OUT A, White : OUT B, Orange : OUT Z, Brown : +V(5VDC, 12–24VDC ±5%), Blue:GND(0V), Shield : F.G
●Line driver output
Black:OUT A, Red:OUT $\overline{A}$, White:OUT B, Gray:OUT $\overline{B}$, Orange:OUT Z, Yellow:OUT $\overline{Z}$, Brown:+V(5VDC ±5%), Blue:GND(0V), Shield:F.G
※Non-using wires must be insulated.
※The shield cable and metal case of encoder must be grounded(F.G).

■Cable outgoing connector type / connector integrated type
●Totem pole output NPN open collector output Voltage output ●Line driver output

| Pin No | Cable color | Function | Pin No | Cable color | Function |
|---|---|---|---|---|---|
| ① | Black | OUT A | ① | Black | OUT A |
| ② | White | OUT B | ② | Red | OUT $\overline{A}$ |
| ③ | Orange | OUT Z | ③ | Brown | +V |
| ④ | Brown | +V | ④ | Blue | GND |
| ⑤ | Blue | GND | ⑤ | White | OUT B |
| ⑥ | Shield | F.G | ⑥ | Gray | OUT $\overline{B}$ |
| | | | ⑦ | Orange | OUT Z |
| | | | ⑧ | Yellow | OUT $\overline{Z}$ |
| | | | ⑨ | Shield | F.G |

○Connector cable
●CID6S-2, CID6S-5, CID6S-10 (Totem pole output/ NPN open collector output/ Voltage output)
●CID9S-2, CID9S-5, CID9S-10 (Line driver output)
※Socket type: C I D 6 S-2 — Cable length (m), Socket type, Number of connector pin, DC power type, I-type, Connector

## Accessary

●Bracket
●Coupling
s = 0.5mm Max. ε = 0.25mm Max. θ = 5° Max.

| Type \ Item | A | B | C | D | E |
|---|---|---|---|---|---|
| φ6mm coupling | φ6 | φ15 | 16.5 | 22 | 4-M3×0.5 |
| φ8mm coupling | φ8 | φ19 | 18.2 | 25 | 4-M4×0.7 |

●When combine the coupling to encoder shaft, if there is big eccentricity or bend between rotating encoder shaft and mate shaft, it may shorten the life cycle of encoder and coupling.
●Use the shaft loading within the rated specifications.

## Output waveform

●Totem pole output/NPN open collector output/Voltage output ●Line driver output
※CW(Clockwise) : As viewed from the shaft

## Caution for using

1. Installation
①Handle the unit with care, it is consisted of precision components.
②Be careful not to make eccentricity and deflection angle larger, it may shorten the life cycle.
③Do not put strong impact when insert coupling into shaft.
2. For using
①Please use attached SIL Twist pair wire and use proper receiver for RS-422A communication.
②Do not connect and cut circuit during power on, or it may cause damage to the unit.
③When use switching power, install the surge absorber in power line and shorter the wire to avoid noise.
3. Environment
Please do not use this unit with below environment, it results in malfunction.
①Place where this unit or component may be damaged by strong vibration or impact.
②Place where there are lots of flammable or corrosive gases.
③Place where strong magnet field or electric noise are occurred.
④Place where is beyond of rating temperature or humidity.
⑤Place where strong acids or alkali near by.
4. Vibration and impact
①When the strong impact loads on this unit, it may cause an error.
②High resolution of encoder can be easily affected by vibration, fix the bracket firmly to install.
5. Wire connection
①Do not draw the wire with over strength 30N after wiring.
②If wire encoder cable with high voltage line or power cable in the same conduit, it may cause a malfunction or mechanical problem. Please wire it separately or use separated conduit.
**※It may cause malfunction if above instructions are not followed.**

## Major products

■ PROXIMITY SENSOR ■ PHOTOELECTRIC SENSOR ■ AREA SENSOR
■ FIBER OPTIC SENSOR ■ DOOR/DOOR SIDE SENSOR
■ PRESSURE SENSOR ■ ROTARY ENCODER
■ SENSOR CONTROLLER
■ SWITCHING POWER SUPPLY
■ TEMPERATURE CONTROLLER
■ TEMPERATURE/HUMIDITY TRANSDUCER
■ POWER CONTROLLER ■ RECORDER
■ TACHOMETER/PULSE(RATE) METER
■ PANEL METER ■ INDICATOR
■ SIGNAL CONVERTOR ■ COUNTER
■ TIMER ■ DISPLAY UNIT
■ GRAPHIC PANEL
■ STEPPING MOTOR & DRIVER & MOTION CONTROLLER

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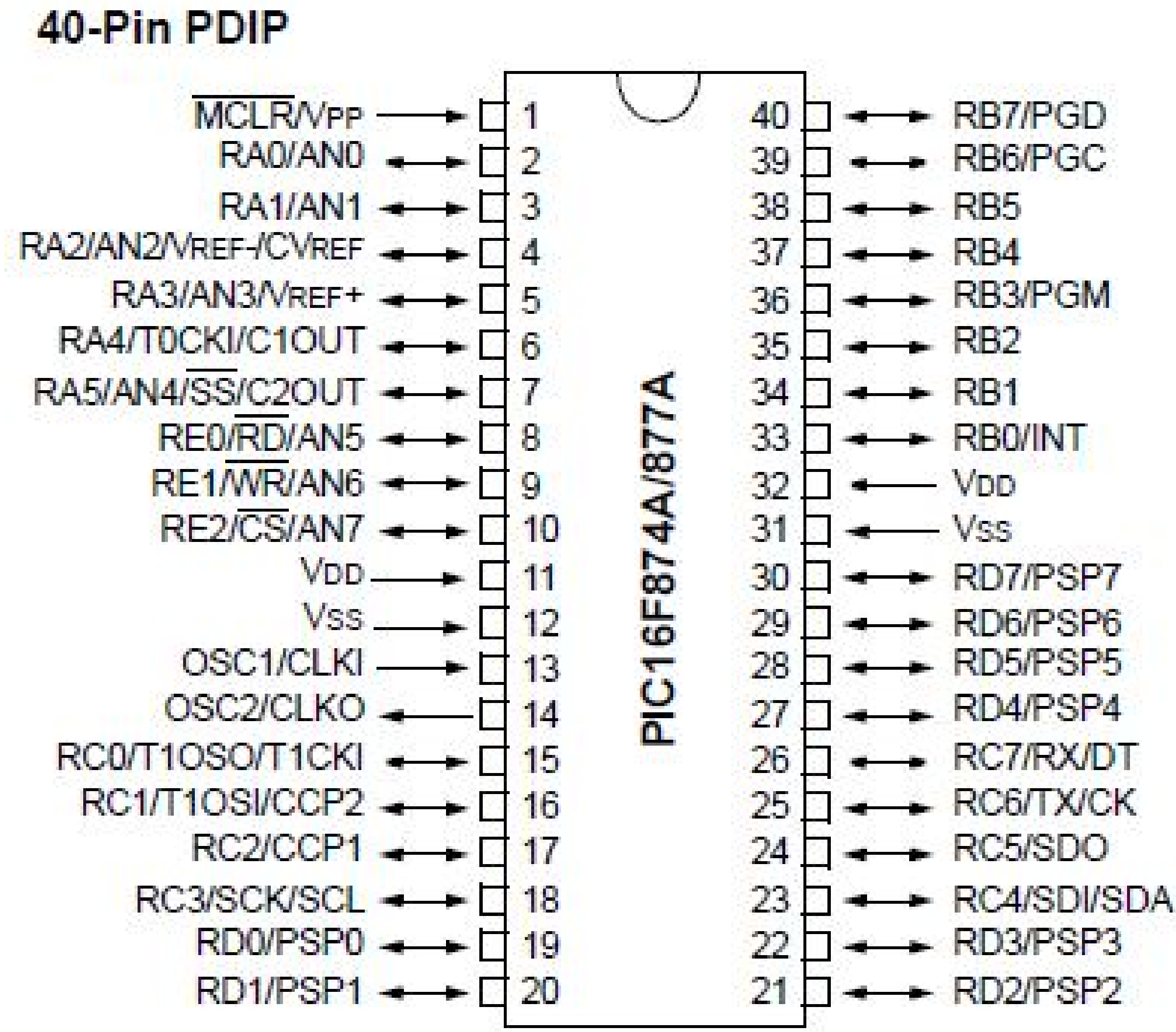
The proposal of a product improvement and development : Product@autonics.com
EP-KE-09-0140

# PIC16F877A

## (Important Pages)


40-Pin PDIP
MCLR/VPP
RA0/AN0
RA1/AN1
RA2/AN2/VREF-/CVREF
RA3/AN3/VREF+
RA4/T0CKI/C1OUT
RA5/AN4/SS/C2OUT
RE0/RD/AN5
RE1/WR/AN6
RE2/CS/AN7
VDD
VSS
OSC1/CLKI
OSC2/CLKO
RC0/T1OSO/T1CKI
RC1/T1OSI/CCP2
RC2/CCP1
RC3/SCK/SCL
RD0/PSP0
RD1/PSP1
PIC16F874A/877A
RB7/PGD
RB6/PGC
RB5
RB4
RB3/PGM
RB2
RB1
RB0/INT
VDD
VSS
RD7/PSP7
RD6/PSP6
RD5/PSP5
RD4/PSP4
RC7/RX/DT
RC6/TX/CK
RC5/SDO
RC4/SDI/SDA
RD3/PSP3
RD2/PSP2

## 4.0 I/O PORTS

Some pins for these I/O ports are multiplexed with an alternate function for the peripheral features on the device. In general, when a peripheral is enabled, that pin may not be used as a general purpose I/O pin.

Additional information on I/O ports may be found in the PICmicro™ Mid-Range Reference Manual (DS33023).

### 4.1 PORTA and the TRISA Register

PORTA is a 6-bit wide, bidirectional port. The corresponding data direction register is TRISA. Setting a TRISA bit (= 1) will make the corresponding PORTA pin an input (i.e., put the corresponding output driver in a High-Impedance mode). Clearing a TRISA bit (= 0) will make the corresponding PORTA pin an output (i.e., put the contents of the output latch on the selected pin).

Reading the PORTA register reads the status of the pins, whereas writing to it will write to the port latch. All write operations are read-modify-write operations. Therefore, a write to a port implies that the port pins are read, the value is modified and then written to the port data latch.

Pin RA4 is multiplexed with the Timer0 module clock input to become the RA4/T0CKI pin. The RA4/T0CKI pin is a Schmitt Trigger input and an open-drain output. All other PORTA pins have TTL input levels and full CMOS output drivers.

Other PORTA pins are multiplexed with analog inputs and the analog VREF input for both the A/D converters and the comparators. The operation of each pin is selected by clearing/setting the appropriate control bits in the ADCON1 and/or CMCON registers.

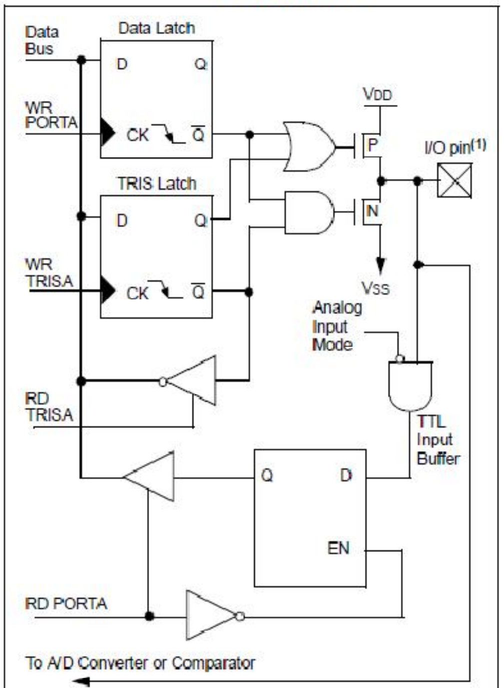
| Note: | On a Power-on Reset, these pins are configured as analog inputs and read as '0'. The comparators are in the off (digital) state. |
|---|---|

The TRISA register controls the direction of the port pins even when they are being used as analog inputs. The user must ensure the bits in the TRISA register are maintained set when using them as analog inputs.

**EXAMPLE 4-1: INITIALIZING PORTA**

```
BCF     STATUS, RP0  ;
BCF     STATUS, RP1  ; Bank0
CLRF    PORTA        ; Initialize PORTA by
                     ; clearing output
                     ; data latches
BSF     STATUS, RP0  ; Select Bank 1
MOVLW   0x06         ; Configure all pins
MOVWF   ADCON1       ; as digital inputs
MOVLW   0xCF         ; Value used to
                     ; initialize data
                     ; direction
MOVWF   TRISA        ; Set RA<3:0> as inputs
                     ; RA<5:4> as outputs
                     ; TRISA<7:6>are always
                     ; read as '0'.
```

**FIGURE 4-1: BLOCK DIAGRAM OF RA3:RA0 PINS**




Note 1: I/O pins have protection diodes to VDD and VSS.

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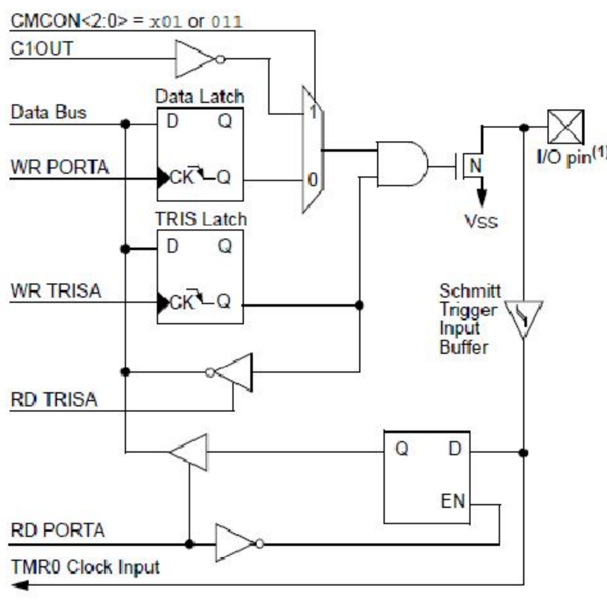
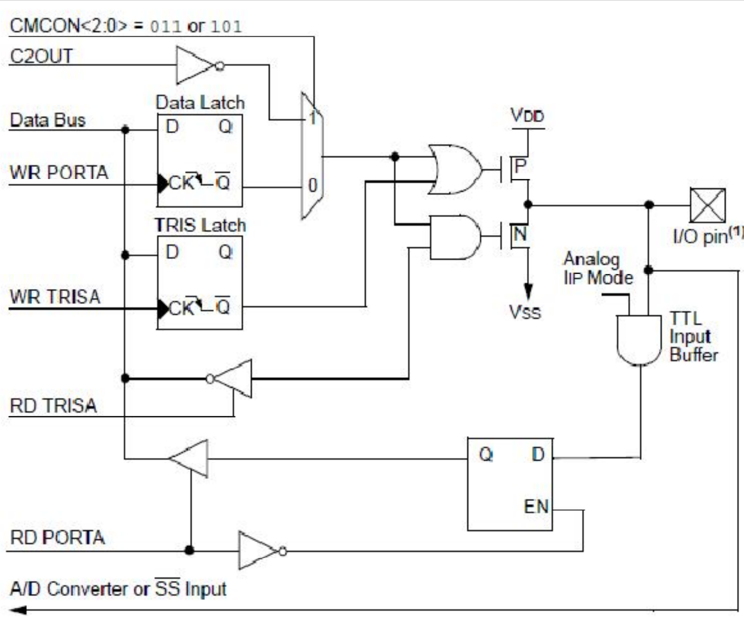
**FIGURE 4-2: BLOCK DIAGRAM OF RA4/T0CKI PIN**




Note 1: I/O pin has protection diodes to VSS only.

**FIGURE 4-3: BLOCK DIAGRAM OF RA5 PIN**




Note 1: I/O pin has protection diodes to VDD and VSS.

**TABLE 4-1: PORTA FUNCTIONS**

| Name | Bit# | Buffer | Function |
|---|---|---|---|
| RA0/AN0 | bit 0 | TTL | Input/output or analog input. |
| RA1/AN1 | bit 1 | TTL | Input/output or analog input. |
| RA2/AN2/VREF-/CVREF | bit 2 | TTL | Input/output or analog input or VREF- or CVREF. |
| RA3/AN3/VREF+ | bit 3 | TTL | Input/output or analog input or VREF+. |
| RA4/T0CKI/C1OUT | bit 4 | ST | Input/output or external clock input for Timer0 or comparator output. Output is open-drain type. |
| RA5/AN4/$\overline{SS}$/C2OUT | bit 5 | TTL | Input/output or analog input or slave select input for synchronous serial port or comparator output. |

**Legend:** TTL = TTL input, ST = Schmitt Trigger input

**TABLE 4-2: SUMMARY OF REGISTERS ASSOCIATED WITH PORTA**

| Address | Name | Bit 7 | Bit 6 | Bit 5 | Bit 4 | Bit 3 | Bit 2 | Bit 1 | Bit 0 | Value on: POR, BOR | Value on all other Resets |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 05h | PORTA | — | — | RA5 | RA4 | RA3 | RA2 | RA1 | RA0 | --0x 0000 | --0u 0000 |
| 85h | TRISA | — | — | PORTA Data Direction Register | | | | | | --11 1111 | --11 1111 |
| 9Ch | CMCON | C2OUT | C1OUT | C2INV | C1INV | CIS | CM2 | CM1 | CM0 | 0000 0111 | 0000 0111 |
| 9Dh | CVRCON | CVREN | CVROE | CVRR | — | CVR3 | CVR2 | CVR1 | CVR0 | 000- 0000 | 000- 0000 |
| 9Fh | ADCON1 | ADFM | ADCS2 | — | — | PCFG3 | PCFG2 | PCFG1 | PCFG0 | 00-- 0000 | 00-- 0000 |

**Legend:** x = unknown, u = unchanged, - = unimplemented locations read as '0'. Shaded cells are not used by PORTA.

**Note:** When using the SSP module in SPI Slave mode and $\overline{SS}$ enabled, the A/D converter must be set to one of the following modes, where PCFG3:PCFG0 = 0100, 0101, 011x, 1101, 1110, 1111.

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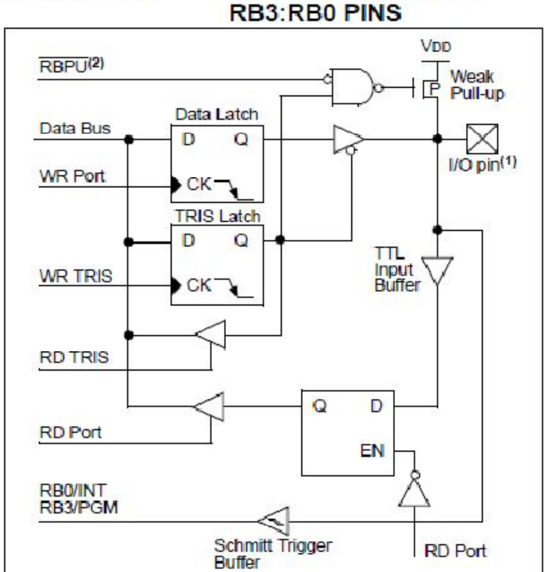
## 4.2 PORTB and the TRISB Register

PORTB is an 8-bit wide, bidirectional port. The corresponding data direction register is TRISB. Setting a TRISB bit (= 1) will make the corresponding PORTB pin an input (i.e., put the corresponding output driver in a High-Impedance mode). Clearing a TRISB bit (= 0) will make the corresponding PORTB pin an output (i.e., put the contents of the output latch on the selected pin).

Three pins of PORTB are multiplexed with the In-Circuit Debugger and Low-Voltage Programming function: RB3/PGM, RB6/PGC and RB7/PGD. The alternate functions of these pins are described in **Section 14.0 "Special Features of the CPU"**.

Each of the PORTB pins has a weak internal pull-up. A single control bit can turn on all the pull-ups. This is performed by clearing bit RBPU (OPTION_REG<7>). The weak pull-up is automatically turned off when the port pin is configured as an output. The pull-ups are disabled on a Power-on Reset.

**FIGURE 4-4: BLOCK DIAGRAM OF RB3:RB0 PINS**




Note 1: I/O pins have diode protection to VDD and VSS.
2: To enable weak pull-ups, set the appropriate TRIS bit(s) and clear the RBPU bit (OPTION_REG<7>).

Four of the PORTB pins, RB7:RB4, have an interrupt-on-change feature. Only pins configured as inputs can cause this interrupt to occur (i.e., any RB7:RB4 pin configured as an output is excluded from the interrupt-on-change comparison). The input pins (of RB7:RB4) are compared with the old value latched on the last read of PORTB. The "mismatch" outputs of RB7:RB4 are OR'ed together to generate the RB port change interrupt with flag bit RBIF (INTCON<0>).

This interrupt can wake the device from Sleep. The user, in the Interrupt Service Routine, can clear the interrupt in the following manner:

a) Any read or write of PORTB. This will end the mismatch condition.
b) Clear flag bit RBIF.

A mismatch condition will continue to set flag bit RBIF. Reading PORTB will end the mismatch condition and allow flag bit RBIF to be cleared.

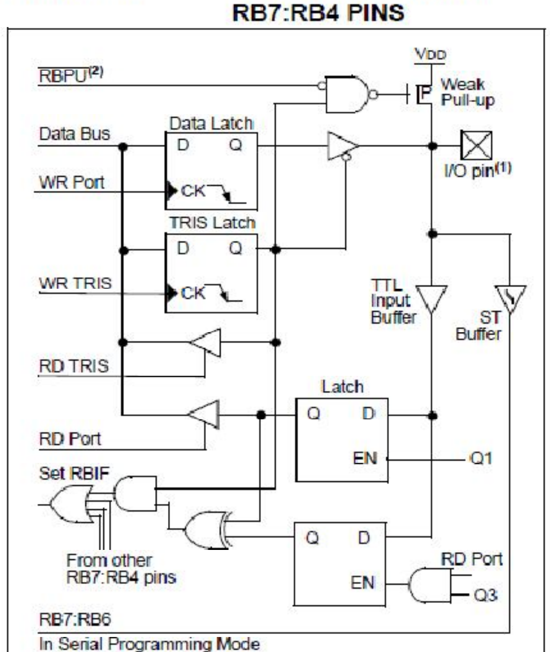
The interrupt-on-change feature is recommended for wake-up on key depression operation and operations where PORTB is only used for the interrupt-on-change feature. Polling of PORTB is not recommended while using the interrupt-on-change feature.

This interrupt-on-mismatch feature, together with software configurable pull-ups on these four pins, allow easy interface to a keypad and make it possible for wake-up on key depression. Refer to the application note, AN552, *"Implementing Wake-up on Key Stroke"* (DS00552).

RB0/INT is an external interrupt input pin and is configured using the INTEDG bit (OPTION_REG<6>).

RB0/INT is discussed in detail in **Section 14.11.1 "INT Interrupt"**.

**FIGURE 4-5: BLOCK DIAGRAM OF RB7:RB4 PINS**




Note 1: I/O pins have diode protection to VDD and VSS.
2: To enable weak pull-ups, set the appropriate TRIS bit(s) and clear the RBPU bit (OPTION_REG<7>).

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**TABLE 4-3: PORTB FUNCTIONS**

| Name | Bit# | Buffer | Function |
|---|---|---|---|
| RB0/INT | bit 0 | TTL/ST(1) | Input/output pin or external interrupt input. Internal software programmable weak pull-up. |
| RB1 | bit 1 | TTL | Input/output pin. Internal software programmable weak pull-up. |
| RB2 | bit 2 | TTL | Input/output pin. Internal software programmable weak pull-up. |
| RB3/PGM(3) | bit 3 | TTL | Input/output pin or programming pin in LVP mode. Internal software programmable weak pull-up. |
| RB4 | bit 4 | TTL | Input/output pin (with interrupt-on-change). Internal software programmable weak pull-up. |
| RB5 | bit 5 | TTL | Input/output pin (with interrupt-on-change). Internal software programmable weak pull-up. |
| RB6/PGC | bit 6 | TTL/ST(2) | Input/output pin (with interrupt-on-change) or in-circuit debugger pin. Internal software programmable weak pull-up. Serial programming clock. |
| RB7/PGD | bit 7 | TTL/ST(2) | Input/output pin (with interrupt-on-change) or in-circuit debugger pin. Internal software programmable weak pull-up. Serial programming data. |

**Legend:** TTL = TTL input, ST = Schmitt Trigger input

**Note 1:** This buffer is a Schmitt Trigger input when configured as the external interrupt.

**2:** This buffer is a Schmitt Trigger input when used in Serial Programming mode or in-circuit debugger.

**3:** Low-Voltage ICSP Programming (LVP) is enabled by default which disables the RB3 I/O function. LVP must be disabled to enable RB3 as an I/O pin and allow maximum compatibility to the other 28-pin and 40-pin mid-range devices.

**TABLE 4-4: SUMMARY OF REGISTERS ASSOCIATED WITH PORTB**

| Address | Name | Bit 7 | Bit 6 | Bit 5 | Bit 4 | Bit 3 | Bit 2 | Bit 1 | Bit 0 | Value on: POR, BOR | Value on all other Resets |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 06h, 106h | PORTB | RB7 | RB6 | RB5 | RB4 | RB3 | RB2 | RB1 | RB0 | xxxx xxxx | uuuu uuuu |
| 86h, 186h | TRISB | PORTB Data Direction Register | | | | | | | | 1111 1111 | 1111 1111 |
| 81h, 181h | OPTION_REG | RBPU | INTEDG | T0CS | T0SE | PSA | PS2 | PS1 | PS0 | 1111 1111 | 1111 1111 |

**Legend:** x = unknown, u = unchanged. Shaded cells are not used by PORTB.

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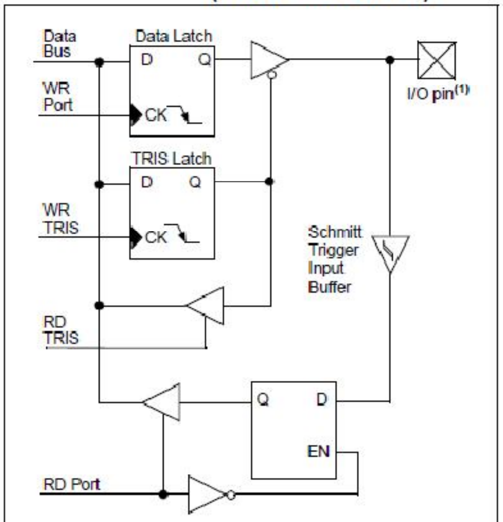
## 4.4 PORTD and TRISD Registers

**Note:** PORTD and TRISD are not implemented on the 28-pin devices.

PORTD is an 8-bit port with Schmitt Trigger input buffers. Each pin is individually configurable as an input or output.

PORTD can be configured as an 8-bit wide microprocessor port (Parallel Slave Port) by setting control bit, PSPMODE (TRISE<4>). In this mode, the input buffers are TTL.

**FIGURE 4-8: PORTD BLOCK DIAGRAM (IN I/O PORT MODE)**




Note 1: I/O pins have protection diodes to VDD and VSS.

**TABLE 4-7: PORTD FUNCTIONS**

| Name | Bit# | Buffer Type | Function |
|---|---|---|---|
| RD0/PSP0 | bit 0 | ST/TTL(1) | Input/output port pin or Parallel Slave Port bit 0. |
| RD1/PSP1 | bit 1 | ST/TTL(1) | Input/output port pin or Parallel Slave Port bit 1. |
| RD2/PSP2 | bit2 | ST/TTL(1) | Input/output port pin or Parallel Slave Port bit 2. |
| RD3/PSP3 | bit 3 | ST/TTL(1) | Input/output port pin or Parallel Slave Port bit 3. |
| RD4/PSP4 | bit 4 | ST/TTL(1) | Input/output port pin or Parallel Slave Port bit 4. |
| RD5/PSP5 | bit 5 | ST/TTL(1) | Input/output port pin or Parallel Slave Port bit 5. |
| RD6/PSP6 | bit 6 | ST/TTL(1) | Input/output port pin or Parallel Slave Port bit 6. |
| RD7/PSP7 | bit 7 | ST/TTL(1) | Input/output port pin or Parallel Slave Port bit 7. |

**Legend:** ST = Schmitt Trigger input, TTL = TTL input

**Note 1:** Input buffers are Schmitt Triggers when in I/O mode and TTL buffers when in Parallel Slave Port mode.

**TABLE 4-8: SUMMARY OF REGISTERS ASSOCIATED WITH PORTD**

| Address | Name | Bit 7 | Bit 6 | Bit 5 | Bit 4 | Bit 3 | Bit 2 | Bit 1 | Bit 0 | Value on: POR, BOR | Value on all other Resets |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 08h | PORTD | RD7 | RD6 | RD5 | RD4 | RD3 | RD2 | RD1 | RD0 | xxxx xxxx | uuuu uuuu |
| 88h | TRISD | PORTD Data Direction Register | | | | | | | | 1111 1111 | 1111 1111 |
| 89h | TRISE | IBF | OBF | IBOV | PSPMODE | — | PORTE Data Direction Bits | | | 0000 -111 | 0000 -111 |

**Legend:** x = unknown, u = unchanged, - = unimplemented, read as '0'. Shaded cells are not used by PORTD.