Designing and Prototype Building of Self-Balancing 'Electric Uni-wheeler' (EUW)

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Abstract - *Stabilization on a single wheel vehicle is a complex task. This paper covers the design, testing, and building of a prototype of a self-balancing vehicle (EUW) capable of carrying a single rider by maintaining the center of gravity of vehicle and rider. The project aimed to design a compact short commute vehicle running on a single electric-motor powered wheel. The capacity of Hub-motor is 350W and the maximum speed can achieve up to 25 km/h. This self-balancing characteristic is achieved by a gyro sensor that reports data of the vehicle body position to a microcontroller (Arduino) and this microcontroller (Arduino) will control the rotation, direction, and speed of hub motor of the vehicle. The main element of this kind of vehicle is the gyro sensor because without it the vehicle is not able to maintain balance.*

Key Words: **Electric Uni-wheeler, Gyro sensor, FEA, PID controller, Hub motor, lead-acid battery.**

1. Introduction

The origin of an idea to create a short commute vehicle for a market that is fairly new and mostly untouched. It inspired me to design 'Electric Uni Wheeler'. Electric Uni Wheeler (EUW) – a self-balancing vehicle came into existence only with the idea to introduce a new way of short-distance transport around many public places and industrial areas as well. It should have safety measures to ensure that the rider feels safe enough to enjoy these short commutes. EUW needs to work on a basic self-balancing feedback system where it can solve theoretical calculation and apply it to the real world.

Electric Uni-wheeler is a single wheel, self-balancing, and battery-powered short-commute electric bike. It has two lead-acid batteries which can be replaced by more efficient and powerful lithium batteries. The electric motor which is used for this project is 'Brush-less DC Hub Motor'. The material used for the vehicle body is AISI 4130 Chromoly steel. It has a tensile strength of 560 MPa. The designing of the body is carried out by CAD software like PTC Creo 4.0 and Solidworks and FEA analysis using Ansys 2019.

The main part of this project is electric circuits and sensors. The PID controller and Gyro sensor are responsible for the operation of the vehicle. Gyro sense the angle and controller control the motor according to the angle of the center of gravity to the vertical plan to maintain the balance of the vehicle, Therefore, to accelerate this bike rider just have to lean forward and to brake, the rider has to lean backward.

The construction of the vehicle has done using advanced engineering techniques. Industrial MIG welding has been used for the joining process. Standard grade fasteners are the only things should be used for joining. After the assembly process testing process comes. In this process, Calculations for vehicle dynamics and static conditions should be verified.

1.1 Objective of the Project

The main objective of the project is to construct a self-balancing single wheel bike. The project is based on short-commute vehicle e.g. moped, bicycle, etc. This vehicle uses gyro technology to maintain the balance of the vehicle. This bike should be accelerated by leaning forward and should be stopped by leaning backward. Therefore, the vehicle will be throttle-free. Turning should be achieved by leaning the body weight in respect of a direction. To develop efficient electric power using existing technology is also an objective of this project.

2. Literature Survey

Vehicles with a single wheel are around us for a longer time than we know. This bike is also considered as a normal cycle in the 19th century. This Monowheel had pedals instead of motors like modern Monowheel. **[4]**

Mechanical and Aesthetic design of existing models like Ryno, Uno Bolt, Rama-Rekto, etc. inspired EUW. The technology of these vehicles is also based on Gyro Technology.

Uno Bolt is an in-production electric unicycle model which was the base inspiration of EUW. Uno Bolt is the world's first bike with gyro force technology. It has a 1000w hub motor with 60v 4.4 Ah li-Fe battery. The frame of the model is fabricated with military-grade alloy steel to increase strength and decrease weight. The range of the model is around 40 km and speed is up to 35 kmph.

Fig -1: Uno BOLT

This design provides a lower center of gravity to reduce effective torque to balance model. Lower seats reduce the possibilities of injuries. Uno bolt is one of the stable models on electric unicycles

Fig -2: Ryno

Ryno is designed to balance itself in pitch direction by using an open feedback system with gyro meter to measure the inclination angle of the model and by using the PID method to reduce, increase or change the direction of rotation of the motor. Ryno is operated by leaning forward or backward. By leaning driver changes the position of the center of gravity and breaks the balance of model, the vehicle moves forward or reverse accordingly to gain balance. **[2]**

To Understand and control operation electrical circuits this paper 'Two-Wheeled Balancing Robot Controller Designed Using PID controller' is necessary to refer. In this paper, a self-balancing two-wheeled robot constructed using Gyro technology. This paper contains information about the calculation done by the PID controller to maintain the balance of the robot. **[2]**

3. Structural Design

This section consists CAD modelling and FEA of the vehicle frame and wheel axle and ergonomic considerations.

3.1 Mainframe

The mainframe is the most important part of any vehicle. This mainframe has been designed according to the triangulation of acting loads and satisfactory ergonomic conditions. All the accessories can be mounted on the mainframe. EUW has only one axle to mount the mainframe. There are slots provided in the mounting plate of the frame to fit the axle. In this frame, Frame members are rigid to each other. The material used for the construction is Chromoly AISI 4130. EUW frame consists of separate space to mount all electrical components like sensors, controllers, batteries, etc. The seating arrangement is restricted to one person due to lots of forces acting to the one point. The design of the seating position is a little bit back from the CG point to balance the vehicle when it turned off.

Fig -3: CAD model of Mainframe

The model has various tube members which have 1-inch diameter and 1-mm thickness. Mounting of the various components is designed that way to occupy less space and weight. The handlebars are designed to provide a comfortable riding position.

3.2 Motor axle

The motor axle is most likely to withstand all the vertical load due to the weight of the mainframe and the rider is concentrated on the two points of the axle. Bending stress is generated at the point of frame mounting so the material of axle must have high bending stiffness and less ductility to withstand dynamic forces.

3.3 Fairings

The purpose of the fairing is twofold. It protects components of a vehicle and it also keeps the user's feet and clothes away from the moving parts, primarily the wheels and drivetrain. The other use of fairing is to provide vehicle nice aesthetic look. The material of fairings is the aluminium sheet with 0.5mm thickness.

3.4 Battery mountings

The position of batteries on the frame is very important. Batteries have mounted at the lower portion of the frame, below the pivot point of chassis. This will counterbalance the load on the upper portion of the pivot point. The weight of the batteries is approx. 24-28 kg and gross vehicle weight are 55kg. Due to the position of batteries, Batteries will act as a simple pendulum and the upper portion of chassis will act as an inverse pendulum. This configuration contributes to stabilizing the vehicle.

3.5 CAD Assembly

Fig -4: CAD Assembly of EUW

As shown in this Figure, EUW consists of various structural components. This is the final rendered image of the CAD model. PTC CREO 4.0 parametric software has been used to design the vehicle. Arrangement of seat height, CG height, electrical circuit positions, fairing, battery mountings, and the mainframe is designed successfully with PTC CREO 4.0.

4. Finite Element Analysis (FEA)

FEA provides data of acting forces on the various component of the vehicle, Here, Total deformation, Equivalent stress at 90 kg load and factor of safety (FOS) of Motor axle and mainframe have calculated. FEA analysis has done with various materials like AISI 4130 steel (Chromoly), Al 7570, etc. Here are the material properties of AISI 4130.

Material Properties	
Ultimate Tensile Strength	560 MPa
Yield Strength	460 MPa
Density	7850 Kg/m^3
Carbon Content	0.28-0.33 %
Bulk Modulus	140 GPa
Poisson's Ratio	0.27-0.3

Table -1: AISI 4130 Steel Material Properties

4.1 FEA analysis of motor axle

Here, the motor axle has tested to vertical force up to 150 kg. Forces have applied at both ends. The material of the axle is considered as AISI 4130.

According to Fig -5, the Total deformation at the both ends of the axle is higher because axle acting as a cantilever beam. Deformation is less than 1mm which is negligible, therefore axle is safe.

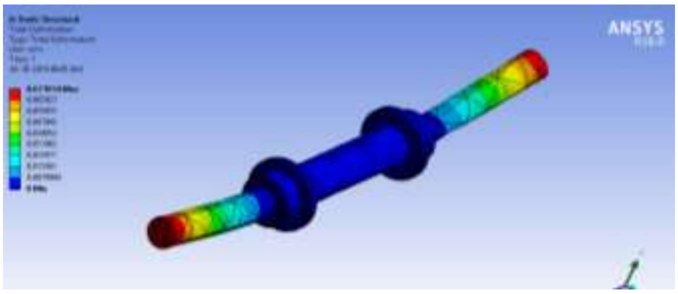

Fig -5: Total deformation at 90 kg load

According to fig. 6, Maximum equivalent stress generates near the fixed support because of the bending of the axle at that point due to the load 90 kg. The value of generated stress is 89 MPa which is very much lower than material properties. Therefore, Axle is safe.

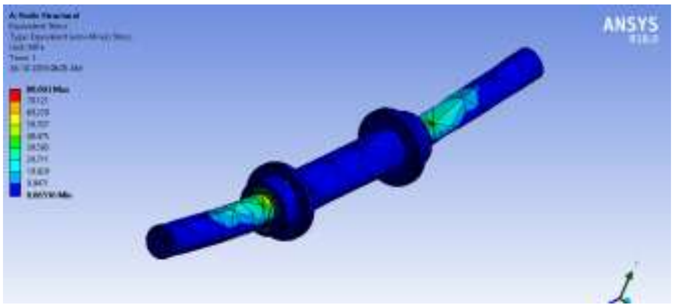

Fig -6: Equivalent stress at 90 kg loading

According to fig.7.8, the Factor of Safety of the axle is more than enough which is nearer to 3 so axle can support 3 times more load than the applied force.

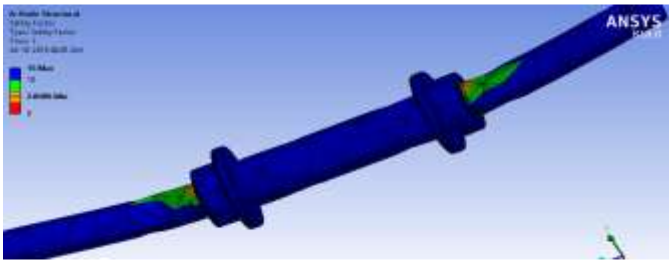

Fig -7: F.O.S at 90 kg loading

According to results axle is safe and nominal deformation occurred which can be neglected.

Test	Loading Weight (Kg)	Total Deformation (mm)	Equivalent Stress (MPa)	FOS
Vertical Loading	90	0.07	89.8	2.8
	110	0.08	108.7	2.2
	130	0.09	123.6	2.0
	150	0.11	143.3	1.7

Table -2: FEA Analysis of Motor Axle

4.2 FEA analysis of Mainframe

The frame is subjected to vertical loading. The weight of the mainframe is 13 kg and the total weight of the vehicle is 50 kg.

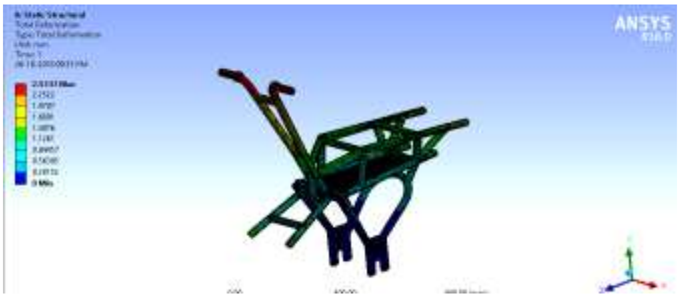

Fig -8: Total Deformation of the frame under 4G force

Here, the Total Deformation of frame is negligible because it is nearer to 1 mm at the base frame. Therefore, Frame is safe.

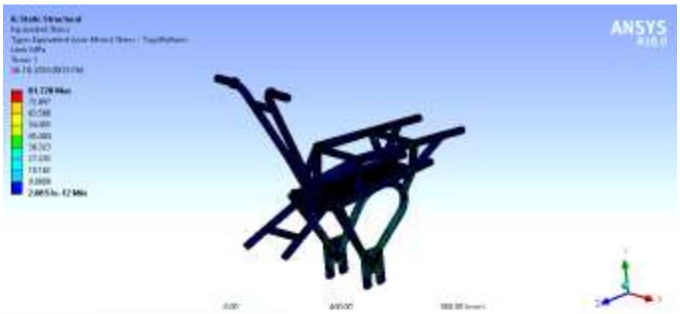

Fig -9: Equivalent stress generated in the frame

Fig-10: Factor of Safety of frame

The maximum equivalent stress generated at the frame is 81 MPa which is safe.

Factor of safety is more than enough to withstand acting forces.

Test	Loading Weight (N)	Total Deformation (mm)	Equivalent Stress (MPa)	FOS
Vertical Loading	4G	2.53	81.72	3
	2G	1.32	35	5

Table -3: FEA Analysis of frames

5. Electrical Components

The selection of all components was done gradually to fulfil requirements of the project including budget, manufacture complexity, the elegance of solution and specifications.

The components in Vehicle is listed below:-

1. Hub motor and wheel
2. Motor controller
3. Battery
4. Microcontroller
5. IMU sensor (Gyro sensor)

5.1 Hub motor and wheel

As BLDC electric hub motor simplified mechanical design considerations, provided a lighter and compact assembly.

Specifications provided by the vendor are as below:-

24V DC operation
Power: 350W
Rated Speed: 300 RPM
Top Speed: 25 Km/h
Nominal Output Torque: 11 Nm
Efficiency: 83%
Weight: 2.5kg

Fig -11: Hub motor of EUW

5.2 Motor Controller

A motor controller is a device that sends a signal to the motor circuit. Therefore, the motor can start and stop. Pulse width modulation is one method to communicate between a micro-controller and a motor controller. By varying width and interval of the pulse, we can achieve forward and reverse motion of the motor.

Fig -12: Motor Controller

5.3 Battery

EUW has 350W 24 V Hub motor and other electrical circuits. The power supply should meet the following project requirements:

1. As compact as possible
2. As light as possible
3. Fast charge rate
4. High discharge capacity
5. Low cost
6. Sufficient charging capacity

According to calculation and requirement, Lithium-ion batteries are a better choice. But, 4 units lead-acid batteries of 12V 9Ah or 5Ah are sufficient.

5.4 Microcontroller

The Arduino Nano is a microcontroller based on the ATmega328. This microcontroller has 32 KB on which we can upload software coding. Arduino has its coding language and a large open-source community to support any projects worldwide. Coding uploaded in the EUW microcontroller is from Arduino open-source. The microcontroller needs a 5-12 v power supply.

Fig -13: Arduino NANO

6. Vehicle Dynamics

6.1 Rolling resistance

Rolling resistance acts between the tire contact patch and the road surface. It resists the wheel to roll freely.

Rolling resistance (R_r) = (a + (b x v)) W kgf

Where, W = Weight of vehicle in a tonne
a, b = Rolling constant (very according to tire type)
a = 7.6
b = 0.5625
v = Velocity in kmph

6.2 Aerodynamic resistance

In the case of EUW, top speed is very low. Therefore, aerodynamic resistance is negligible.

6.3 Gradient resistance

The resistance provided by the gradient surface is known as gradient resistance.

Gradient resistance (Rg) = W x sinθ

Where, W= Weight of the vehicle
θ = Angle of gradient

6.4 Total resistance

Total resistance is the summation of all the resistance acting on the vehicle. Total resistance must be overcome by total driving torque which is provided by DC motor.

Total resistance (R_T) = Rolling resistance (Rr) + Gradient resistance (Rg)

Sr. No.	Vehicle Speed(Kmph) / Slope angle (θ)	Rolling Resistance (R_r) N	Gradient Resistance (Rg) N	Total Resistance (R_T) N
1	0	0.87	0	0.87
2	5	0.90	4.79	5.69
3	10	0.93	9.50	10.43
4	15	0.95	14.23	15.18
5	20	1.00	18.81	19.81
6	25	1.03	23.24	24.27
7	30	1.06	27.50	28.56

Table -4: Resistance table

EUW has enough driving torque to overcome the resistance forces.

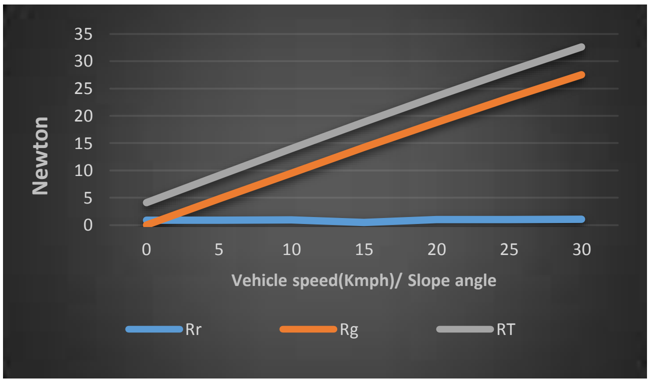

Chart -1: Resistance chart

7. Control System Design

The Control system is designed using the following stages:-

1. First, a mathematical model of the systems derived, it has to be more accurate.
2. The system is identified by analyzing the model and its response to various inputs
3. According to the result of the previous step, a suitable control system can be designed.
4. Finally, when the actual device available, the control system is implemented into hardware.

The most common type of controller used is the classical PID (Proportional Integral Derivative). A PID controller is generally used to regulate an input and output signal. The control signal is generated by applying three gains to the input error and summing the result. [5]

The transfer function K(s) of a PID controller is

$K(s) = K_p + K_d\, s + (K_i/s)$
$= (K_d S^2 + K_p S + K_i)/S$
$= (K_p T_d S^2 + K_p S + T_i K_p)/S$
$= K_p ((T_d S^2 + S + T_i)/S)$

Here, K_p = the proportional gain.
K_i = the integral gain.
K_d = the derivative gain.
T_i, T_d = Time constant.

While designing the control system for EUW the potentiometers were set to inspect the operation of the board. The microcontroller reads the analog values from the potentiometers and consequently refreshes the values of the PD constants. Every constant affects the system in different ways:-

- Increasing K_p promotes rise time while worsening settling time.
- Increasing K_d improves rise time and settling time (to a point).
- Increasing K_i enhances steady-state error but can have disadvantageous influences on the controller.

The Integral constant was decided to hold constant. While it enhances the steady-state error, a small mismatch heads to its dominance over other constants, which makes the system react rather eccentrically to input values. These steps are necessary to tune PD constant

- Established $K_p = K_d = 0$.
- Regulate K_p until the system gains balance, but rapidly oscillates around an equilibrium.
- Alter K_d until the system reaches a steady-state.

7.1 Principle of Operation

EUW works on the principle of an inverted pendulum. The first step to design EUW requires a mathematical model. The forces acting on the wheels include forces due to contact with the ground, horizontal disturbance, weight, reactions with the torque applied by the motor. The forces on the frame include force that a person would apply to the post when tilting forward or backward.

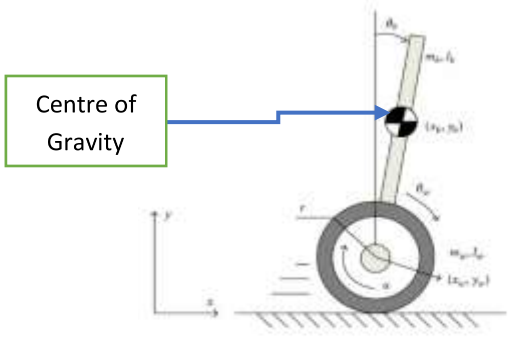

Fig -14: Inverted Pendulum with Centre of Gravity

In fig -14, Mathematical model of EUW shown which works on inverted pendulum principle. In inverted pendulum, Mass of vehicle accumulated above the pivot point. Whenever there is an inclination in the axis of CG obtained, Cart tries to revert to normal by accelerating in that direction. All these conditions can be applied to EUW.

To make the model simpler, we assume the following:-

1. There are no lateral forces, so the forces we consider in two-dimensional space.
2. The friction between W and the ground is high enough for the wheel.

8. Electrical diagram and Methodology

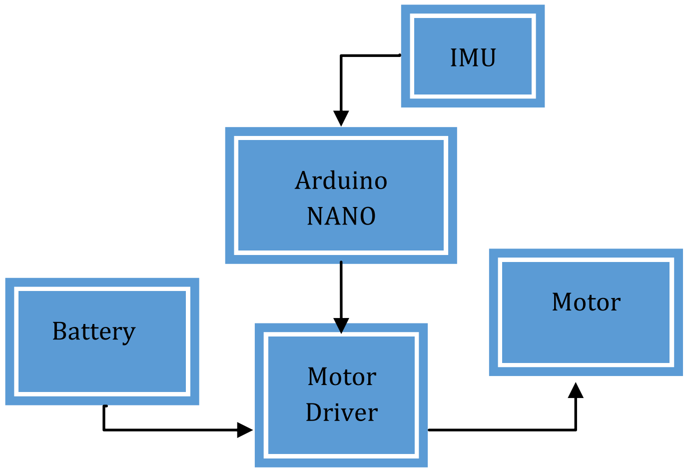

Chart -2: Electrical block diagram

As shown in the diagram, The IMU sensor which is MPU6050 calculates the angle of inclination with to the vertical axis and sends it to the Arduino NANO. Arduino calculates the data according to the coding in which maximum and minimum leaning angles are provided. IMU sensor is mounted on a horizontal surface so if the angle is less than 180°, Motor will move forward and if it is more than 180°, Motor will move reverse or stop.

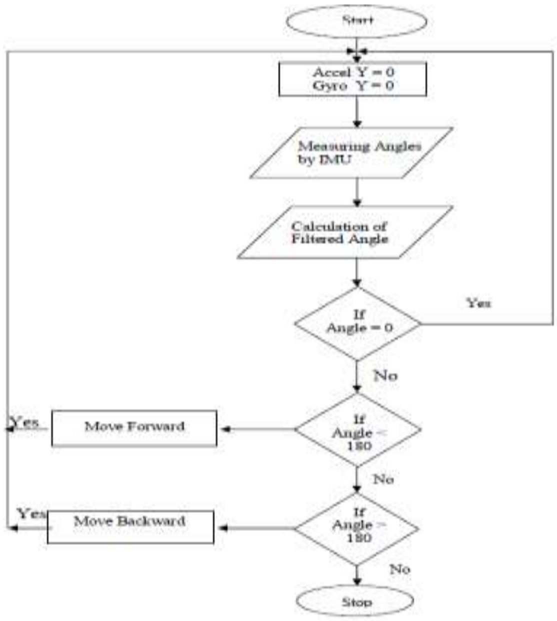

Chart -3: Flow chart of the operation of electrical circuits

9. Cost Analysis

All values are in INR.

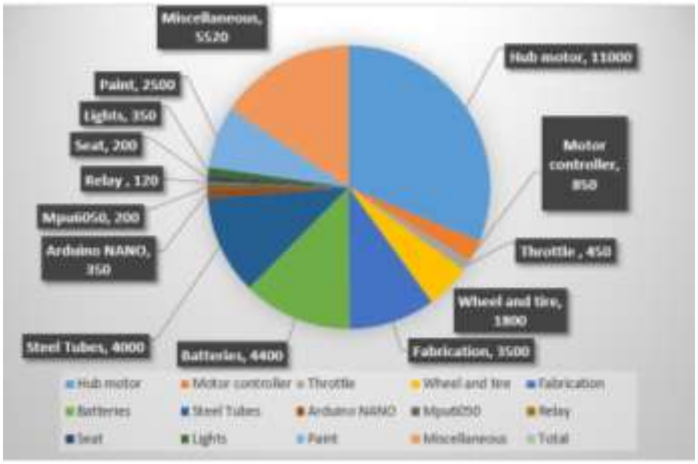

Chart -4: Cost Analysis in Pie chart

10. Conclusion and Result Discussion

To conclude, the Construction of the frame and assembly can be done very easily with the help of modern engineering techniques. Coding using Arduino open-source data is very easy but if it can be modified according to requirement, it is very easy. The Self-balancing code from open-source website is successfully implemented.

Fig -16: Prototype of self-balancing Electric Uni- Wheeler

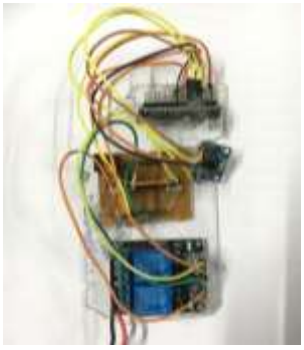

Fig -17: Electrical Circuit

Balancing on a single wheel is achieved using gyro technology. More efficient operation can be achieved by using lithium-ion batteries and more reflexive and power-efficient motor.

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