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Design and Fabrication of a Self Balancing Transportation Device

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***Abstract*— The Self balancing human transportation system is a small footprint electrical vehicle designed by Dean Kamen to replace the car as a more environmentally friendly transportation method in metropolitan areas. The dynamics of the vehicle is similar to the classical control problem of an inverted pendulum, which means that it is unstable and prone to tip over. The problem of unstability and tipping over can be prevented by using sensors which sense the pitch angle and its time derivative, controlling the motors to keep the vehicle balancing. This kind of vehicle is interesting since it is relevant to an environmentally friendly and energy efficient transportation industry. This device can be used for transportation over small distances.**

Keywords*— electric vehicle, inverted pendulum, pitch angle, energy efficient.

I. INTRODUCTION

With the recent developments of usage of sensors and electronics in a synergistic combination with the mechanical developments has led the emergence of innovative field of Mechatronics. This field has found itself a very prominent place in production, manufacturing, robotics etc. But in 2001, this field found itself a great application in the transportation field when DEAN KAMEN designed the "SEGWAY" a self balancing transportation device. Companies have constantly tried to make pollution free vehicles or environmentally friendly vehicles. Since the beginning of 21st century, air pollution, global warming, and the need of preserving conventional resources has pushed the designers to design green powered vehicles [6].

The self balancing vehicle is designed with intention for easy city transportation and can be considered as a small platform for experimentation by the engineers. This vehicle is also designed keeping in mind the ever increasing problem of air pollution and global warming. The Self balancing personal transportation device was introduced in the year 2001 by Dean Kamen [6]. It is commercially manufactured by Segway Inc. of New Hampshire, USA [1].

The Segway HT is a vehicle which has two coaxial wheels driven independently by a controller that balances the vehicle both with and without a rider. The balancing is regulated by feedback from an array of tilt sensors and gyroscopes [9]. The self balancing human transportation device is based on the principle of inverted pendulum that will keep an angle of zero degrees with vertical at all times [2].The device uses combined gyroscopic and accelerometer sensor to detect the motion of the rider so the vehicle can accelerate, brake or steer. This project uses combined fundamentals of mechanics, vehicle dynamics, control systems and programming [9]. This self balancing device uses Arduino Uno controller board, gyroscopic sensors and accelerometers and battery powered electric motors. This vehicle is a two coaxial wheeled device running on battery powered motors.

The device has no brakes or accelerator, but has a handgrip for making turns. It is the only vehicle able to turn in place, just like a person, because its wheels have the ability to turn in opposite directions. For two-wheeled self balancing robots, stability is vital as they cannot remain upright (balanced) without effort [4].

II. OPERATING PRINCIPLE

A. *Concept of self balancing in Vehicle*

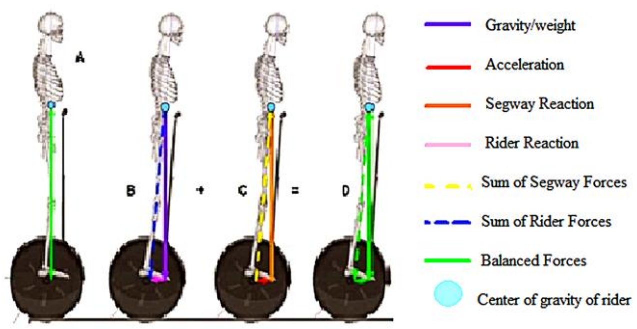

Fig. 1: Free Body Diagram (FBD) for the Self-Balancing principle [2]

The balancing action of Segway is as explained above. In Fig. 1 the Diagram A, on the left it shows that the rider standing, with gravity and the Segway reaction force in balance. In diagram B the rider has leaned forward to start moving. The purple arrow is weight. The magenta arrow is the reaction force of rider against the Segway. The dashed blue line is the vector sum of the two. If the Segway doesn't respond rider will fall forward as the Segway is pushed backward. Diagram C shows the response of the Segway as it senses the tilt of the Segway platform as the rider leans forward.

The computers order the motors to power the wheels and accelerate the Segway. The force of acceleration is the red arrow, and the reaction force of the Segway to rider is the orange arrow. The dashed yellow line is the vector sum of the two forces. Diagram D shows that the sum of the forces in diagrams B and C are in balance. The vector sums run through each other and the rider, so there are no unbalanced forces or torque. The onboard computers adjust the power to the wheels to keep the forces balanced through the rider. This how the Segway balances itself [2].

A. Analogical concept for self balancing

The balancing technology for operation of this device was invented to mimic in such a way as the human body balances itself. The balancing mechanism operates like how the fluid in the inner human ear sends signals to the brain when the body shifts.

If you stand up and lean forward so that you are out of balance you probably will not fall on your face because your brain knows you are out of balance due to the shift of fluid so it triggers you to put your legs forward and stop the fall. If you keep leaning forward the brain will keep putting your legs forward to keep you upright. Instead of falling you will walk forward one step at a time [7].

Now the self balancing human transportation device does very much the same thing except the wheels act like legs a motor instead of muscles and the collection of micro processors act like brain. Also a set of sophisticated tilt sensors act like an inner ear fluid balancing system so just like the brain this device knows when you are leaning forward.

III. OBJECTIVES

The main purpose was to design and construct a fully functional two wheeled balancing vehicle which can be used as a means of transportation for a single person. It should be driven by natural movements; forward and backwards motion should be achieved by leaning forwards and backwards. Turning should be achieved by tilting the handlebar sideways. To provide untethered operation the vehicles' energy source was designed to be a battery. One of the goals was to implement easy recharging of this battery.

A. Vehicle goals:

a. Speed should be controlled by the rider leaning forwards and backwards.
b. Turning should be controlled by tilting the handlebar.
c. Balance and transport persons weighing up to 100 kg.
d. Drive continuously for 60 minutes or 15 km, whichever comes first. Be rechargeable from a standard 220V 50Hz wall socket.
e. The device should be portable and economical in cost.

B. Economic Considerations:

a. No extra finish like paint and plastic details will be done.
b. The motor controllers will be bought, no construction in this area will be made.
c. The mathematical model will not be made entirely from scratch. Instead other models will be evaluated and then finally one of them will be used with necessary modifications to fit the project.

IV. METHODOLOGY

For the development of this device the following flowcharts explain the working of the device:

A. Operation of device:

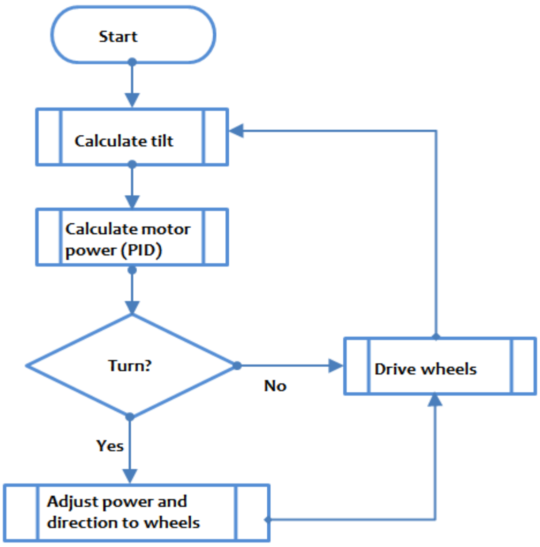

Fig. 2: Flow-Chart of basic operation of the device [8]

B. Electronics Flow Chart:

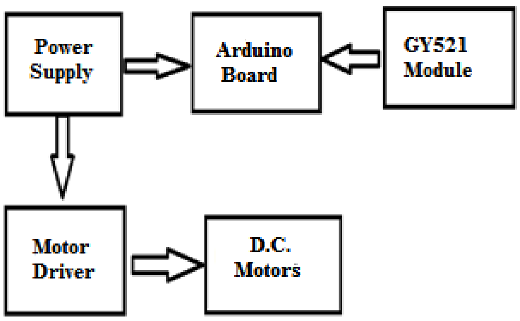

Fig. 3: Electronics Flow-Chart [2]

Co-relating Fig 2&3, Tilt will be calculated using GY521 module. The power to be supplied from the motor to the wheels will be calculated by Arduino board. A motor driver is used for steering purpose.

V. ELECTRONICS

The control system and the sensors play a very important role in the operation of the device. The electronic components used are as enlisted below:

A. GY521 module:

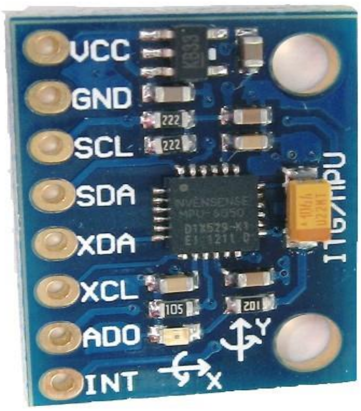

Fig. 4: GY521 module MPU6050 [3]

The InvenSense MPU-6050 sensor contains a MEMS accelerometer and a MEMS gyro in a single chip. It is very accurate, as it contains 16-bits analog to digital conversion hardware for each channel. Therefore it captures the x, y, and z channel at the same time. The sensor uses the I2C-bus to interface with the Arduino [3].

1. Accelerometer:

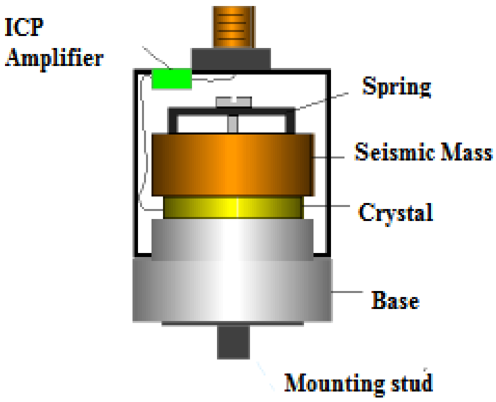

Fig. 5: Accelerometer [12].

An accelerometer is a sensor device capable of sensing acceleration. These sensors may be built in numerous different ways. In modern applications where low cost and small size is important, the microelectromechanical system (MEMS) type accelerometers present a feasible option. MEMS devices began appearing on the commercial market in the late 80's and has since evolved into extremely light weight, cheap miniature sensors with the same accuracy as traditional techniques which are larger and more costly . A modern accelerometer often includes a spring loaded structure whose deflection in response to external forces can be capacitively sensed and converted to an electrical signal [10]. In balancing vehicles where the pitch angle is of interest the accelerometer can be used to measure the orientation of the vehicle with respect to gravity. The gravitational force will affect the spring loaded structure and the sensor sends a signal representing the acceleration along its sensing axis.

The drawback of accelerometers for pitch angle estimation in vehicles is that they are affected by linear acceleration occurring naturally while driving as well as rotational acceleration if the sensor is placed with a distance to the vehicle's rotational axis [6].

2. Gyroscope:

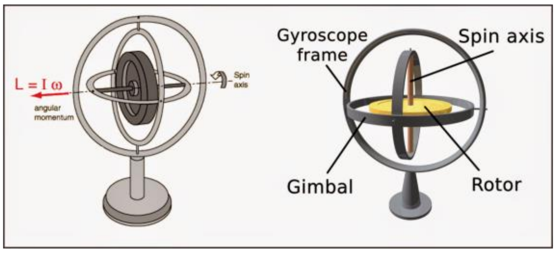

Fig. 6: Gyroscope [14]

A gyroscopic sensor (gyro) is used to measure the angular rate of an object with respect to an inertial system. They are commonly of micro electro-mechanical systems (MEMS) type like the accelerometers discussed in the previous section if low cost and small size is desirable. The mechanical system used for sensing may vary, but a common type uses two vibrating masses to measure the Coriolis acceleration. The Coriolis acceleration comes from rotational motion and by capacitively sensing the distance between the vibrating masses, the amount of Coriolis acceleration they are affected by can be deduced. This allows the angular rate to be calculated. The gyro output signal can also be integrated to find the angle of the motion. This estimate will be less affected by linear acceleration than the accelerometer output, but will suffer from drifting when numerical integration is used [6].

Gyro sensors also suffer from bias, meaning that the output when completely still is not equal to zero. This bias can be dependent on temperature, vibrations, sensor supply voltage etc. and is therefore extremely hard to predict and remove, and will also add to the drift of the angle estimation [11].

B. Arduino Uno:

Arduino is an open source computer hardware and software company, project and user community that designs and manufactures microcontroller-based kits for building digital devices and interactive objects that can sense and control objects in the physical world.

The project is based on microcontroller board designs, manufactured by several vendors, using various microcontrollers. These systems provide sets of digital and analog I/O pins that can be interfaced to various expansion boards ("shields") and other circuits. The boards feature serial communications interfaces, including USB on some models, for loading programs from personal computers. For programming the microcontrollers, the Arduino project provides an integrated development environment (IDE) based on the Processing project, which includes support for the C and C++ programming languages [3].

C. L298N Motor driver:

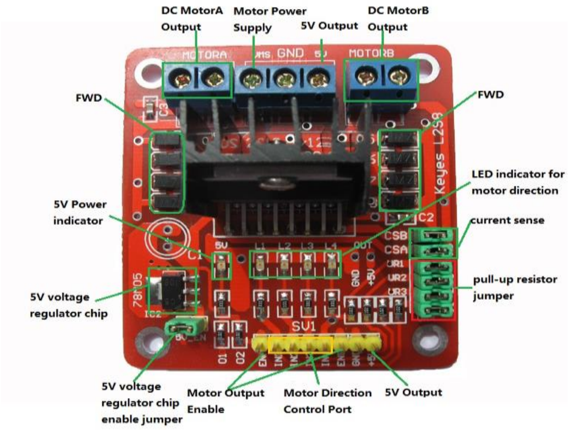

Fig. 8: Motor Controller [13]

The L298N is a high voltage, high current, dual full-bridge motor driver designed to accept standard TTL logic levels and drive inductive loads such as relays, solenoids, DC and stepping motors.

Features:

1. Driver chips: new and original dual H-bridge driver IC L298N.
2. Power-driven part of the terminal range of VMS: +5 V ~ +30 V.
3. Drive some peak current Io: 2A.
4. Maximum power consumption: 25W.
5. Other functions: control the direction indicator, power indicator, current detection, the logic part of the board to take power interface.

VI. Mechanical Components

A. Chassis:

The chassis will be of tubular frame. Various material options were available of which CHROME-MOLY STEEL was selected as the main aim is to make the device portable. So it is necessary to reduce the weight wherever possible. These pipes provide higher strength at a lower weight. The main characteristics are strength (creep strength and room temperature), rigidity, hardenability, wear resistance, corrosion resistance, fairly good impact resistance (toughness), relative ease of fabrication that makes it a “perfect fit” for this application.

B. DC Motor:

Two 12V DC Motors are fixed with the chassis through screwed bolts and it is the main source of power to drive the vehicle. There are two motors, each for one wheel. The motors are driven by two 12 V batteries arranged in series.

C. Base Plate and Handle:

The Base plate and Handle are also important mechanical components in the system. The base plate will be made of Marine Ply which has excellent strength, low cost and high damping capacity. The Marine ply will be coated with the Checkered Sheet Metal so that the rider can maintain balance at all times. The material selected for handle will be made up of PVC tubings. At the top of the handlebar it will be covered with polystrene material so that the rider can have a better grip while riding.

D. Chain drive:

Chain drives are used to transmit power between motor and wheel. Type of chain used is Power transmitting chains (Bush Roller Type).

Chain drives are used because it has the following advantages:

1. No slip
2. Occupy less space
3. High transmission efficiency
4. Highly preferable for small shaft distance

VII. DESIGN OF COMPONENTS

1)*Chassis*:

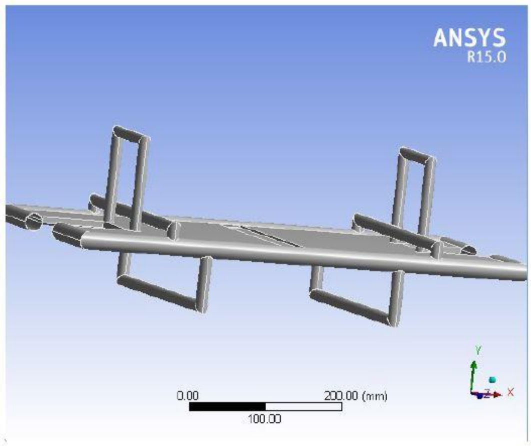

Fig. 9: 3D CAD Model of Vehicle Chassis.

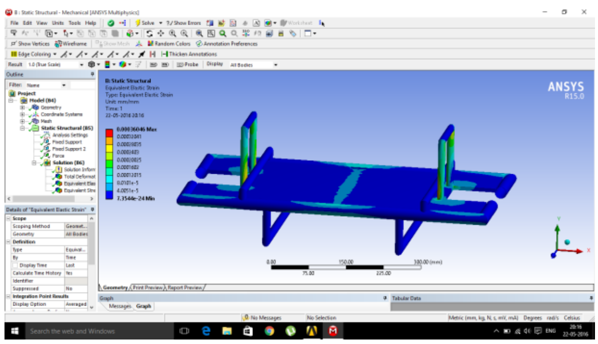

Fig. 10: Total Equivalent Strain on Chassis.

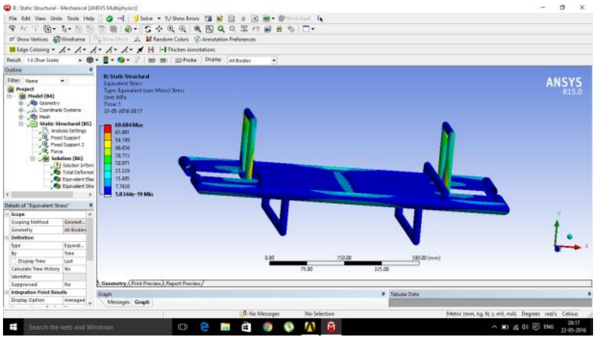

Fig. 11: Total Equivalent Stress on Chassis.

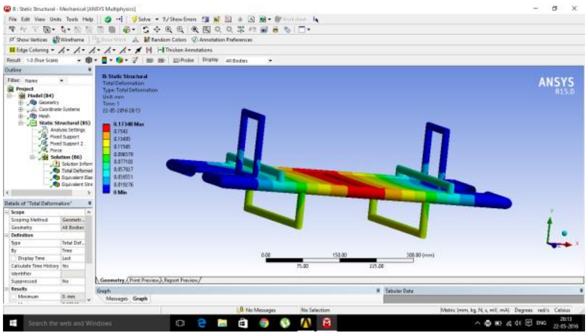

Fig. 12: Total Deformation

TABLE 01
Structural Steel > Constants

Density	7.85e-006 kg mm^-3
Coefficient of Thermal Expansion	1.2e-005 C^-1
Specific Heat	4.34e+005 mJ kg^-1 C^-1
Thermal Conductivity	6.05e-002 W mm^-1 C^-1
Resistivity	1.7e-004 ohm mm

TABLE 02
Structural Steel > Compressive Ultimate Strength

Compressive Ultimate Strength MPa
0

TABLE 03
Structural Steel > Compressive Yield Strength

Compressive Yield Strength MPa
250

TABLE 04
Structural Steel > Tensile Yield Strength

Tensile Yield Strength MPa
250

Structural Steel > Tensile Ultimate Strength

Tensile Ultimate Strength MPa
460

TABLE 05
Structural Steel > Isotropic Secant Coefficient of Thermal Expansion

Reference Temperature C
22

TABLE 06
Structural Steel > Alternating Stress Mean Stress

Alternating Stress MPa	Cycles	Mean Stress MPa
3999	10	0
2827	20	0
1896	50	0
1413	100	0
1069	200	0
441	2000	0
262	10000	0
214	20000	0
138	1.e+005	0
114	2.e+005	0
86.2	1.e+006	0

2) *Suspension System*:

Fig. 13: Suspension Assembly

CALCULATIONS:

Consider the vehicle moving over a rough road which is a case of support motion excitation. Distance between adjacent crest and trough is known as wavelength "λ"

m = mass of vehicle (neglecting unsprung mass)

T = time taken by the vehicle to cover the distance

Time period (T) = $2\pi/\omega$ ……………… (1)

We know that, v = λ/t………………… (2)

From (1) and (2);

$2\pi/\omega = \lambda/t$

As we know λ of the road excitation frequency "ω" can be calculated. Now if we know the speed of the vehicle 'v' and vice versa

As per our data;

m=110 kg

k=1100 lbs/inch = $192.64*10^3$ N/m

Assume ε = 0.5

V= 5 m/s

Assume λ = 6m

Y=0.05

Hence 2π/ω = λ/v

$$\frac{2\pi}{\omega} = \frac{6}{5}$$

ω = 5.235 rad/s

$$\omega_n = \sqrt{\frac{K}{m}}$$

ω_n = 18.71 rad/sec

$$r = \frac{\omega}{\omega_n}$$

r = 0.279 < 1.414

Calculating amplitude X

$$\frac{X}{Y} = \frac{\sqrt{1 + (2 * \varepsilon * r)^2}}{\sqrt{(1 - r^2)^2 + (2 * \varepsilon * r)^2}}$$

$$\frac{X}{Y} = 1.0775$$

X= 0.05387m

X = 53.87 mm

As x was around 5 cm therefore we reduced the stiffness of the spring for which the amplitude is around 2 – 2.5 cm.

Suspension material: Aluminium iron alloy.

TABLE 07
Structural Steel > Strain-Life Parameters

Strength Coefficient MPa	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient MPa	Cyclic Strain Hardening Exponent
920	-0.106	0.213	-0.47	1000	0.2

TABLE 08
Structural Steel > Isotropic Elasticity

Temperature C	Young's Modulus MPa	Poisson's Ratio	Bulk Modulus MPa	Shear Modulus MPa
	2.e+005	0.3	1.6667e+005	76923

TABLE 09
Structural Steel > Isotropic Relative Permeability

Relative Permeability
10000

3) *Motor power calculations*:

Fig. 14: Hub motor & Wheel Assembly

The specifications of Hub motors are as follows:

Motor type: Brushless Direct Current (BLDC).

Voltage: 36 volts

Power: 350 watts

Wheels: 10 inch

Speed: 488 RPM

Net Weight: 3.2 kg each

Tyre type: Pneumatic tyres

Nominal output Torque: 7.827 N-m.

BASIC CALCULATIONS:

1) m = 110 kg
2) v = 18 km/hour = 18*5/18 = 5 m/second
3) r = 0.13 m
4) ω = v/r = 5/0.13 = 38.46 rad/seconds
   Now we know that,
5) ω = (2*π*N)/60

   38.46 = (2*π*N)/60

   N= 367.26 RPM
6) F = m*a

   a = Δv/Δt

   a = (5-0)/(5-0)

   a = 1 m/sec^2

   F = 110*1

   F = 110 N
7) E = 0.5*m*v^2

   E = 0.5*110* 25

   E = 1375 Joules
8) P = E/t

   P = 1375/5

   P = 275 Watts.

Therefore selecting next standard higher rating of motor power i.e. 350 watts.

VIII. COSTING OF THE DEVICE

Material	Cost	Qty.
API 5L X70 Steel (OD 24mm, 1.5 thick)	Rs.2236 (5ft. rods)	2
Aluminium Blocks	Rs. 178	4
Acrylic Sheet(2*3ft)	Rs.400	1
Fabrication cost	Rent	Labour
Lathe Machining	Rs.600	Rs.600
Welding	Rs.420	Rs.0
Cutting & Grinding	Rs.550	Rs.0
Assembly	Rs.0	Rs.0
Electronic Component	Cost	Qty.
Motor Controller	Rs. 3000	1
MPU 6050	Rs.1500	2
Motor (36V 350W)	Rs. 6500	2
Battery (36V)	Rs. 2500	1
Battery Charger	Rs. 1800	1
Equipments & Inventory	Cost	Qty.
Shock Absorbers	Rs.500	2
Rivet Gun	Rs.457	1

IX. APPLICATIONS

1. This personal transporters are becoming more popular as gas prices rise and variety of its uses are found.
2. Helps staff in various roles to travel throughout large bases and vast facilities quickly allows riders to easily travel indoors, outdoors, through doorways and into elevators.
3. Military bases are very large properties which are often home to dozens of buildings. It can take an airman on this device 20 minutes to travel the same distance that would take him 45 minutes to walk. That type of increase in efficiency is valuable.
4. Elevates the visibility, responsiveness and productivity of critical staff.
5. Securities in malls using this vehicle for patrolling is an increasing sight nowadays.

X. FUTURE SCOPE

To enhance the functionality and performance of the vehicle there are some areas that could be developed further:
1. Shielding of the steering sensor signal and/or replace the sensor with a less disturbance sensitive sensor.
2. Proper Cushioning of the IMU to reduce the impact of disturbances.
3. Add communication to a web server for logging of data.
4. Bluetooth communication for remote control and remote logging of data.
5. Employing a new remote control mode for the vehicle without rider.

CONCLUSION

Thus we have developed a working model of this self balancing transportation device similar to SEGWAY which is portable and economical using open source microcontrollers and sensors. This project is implemented with an idea to find an effective solution to transportation problem. The main objective is to achieve space utilization and minimize the fuel consumption especially for commuting over shortest distance.

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