

## Design and Simulation of a Two-Wheeled Inverted Pendulum - a Balanced, Easy Moving Vehicle for the Material Handling

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**Abstract:** Inverted pendulum has attracted many researchers recently because of its demand for the present industries. Actually the earlier works were made attempts for human transport. This paper deals with design and simulation of a two-wheeled, inverted pendulum (TWIP). It is a balanced, easy moving vehicle, which covers the modeling and design of a co-axial, two wheeled vehicles to provide a method of material transport. The behaviors considered is similar manner two wheeled human transporting vehicles. The ANSYS was used to calculate the stress situations on each component. In the end the simulation was done to show that a rider could travel without falling. The simulations were separately created for the straight path and also for the curved path. All the problems and obstacles which were faced during this time were addressed in a methodical manner to achieve both feasible and practical solutions. The outcomes of a range of previous attempts at creating self-balancing devices are discussed. The design of this vehicle draws upon the advantages and disadvantages of the previous design in an attempt to create a robust, easy to use device. Components for the device were selected after extensive research had been made and the mechanical and electrical design was implemented using the characteristics of these components. The process used to maintain the scooter in the upright position, is similar to that used by humans to balance. By recognizing the angular position the device is from upright, a correction is made using a state space controller, which moves the wheels in the appropriate direction to return the device to the original upright position.

**Key words:** Inverted pendulum • Simulation • Material handling • Fixed path • Curved path

### INTRODUCTION

In the past couple decades, there were many literatures were presented in the study of inverted pendulum [1-8]. The two-wheeled inverted pendulum is a best choice for meeting present industrial and social requirement. The TWIP has such significance and suitability like zero radius turning ability, agility in narrow spaces and crowded conditions and left a small footprint, etc. hence the two-wheeled inverted pendulum has become a research hotspot recently. In case of growing more and more congestion due to serious city traffic, the Inverted pendulum robot is a best choice for a city commuting or a patrol transporter. The two-wheeled, inverted pendulum can also be chosen for the service robot platform because of its menu variability and consuming less space while operation [9].

The two-wheeled, inverted pendulum type robot is an under-actuated Non-linear system, for teaching or a research platform for investigating advanced control methods [10-12]. Mr. Grasser [13] developed a prototype of a revolutionary two-wheeled, inverted pendulum vehicle with the configuration of two coaxial wheels. The each wheel was coupled to Direct Current motor and the pendulum vehicle is facilitated to make stationary or U-turns. The system was kept equilibrium by pilot motors and two decoupled state-space controllers.

The final prototype JOE-Inverted pendulum shown in Figure 1. Grasser *et al.* [13] imagine a form of human transport whereby the driver balances on two coaxial wheels, however, they decided to begin with a scaled down prototype with a fixed weight replacing the human driver. This led to “reduced costs and removed the risk to test pilots” whilst the simplified model eliminated many



Fig. 1: JOE-Inverted pendulum [13]

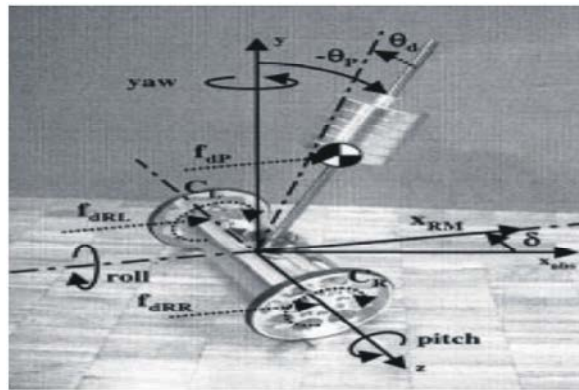


Fig. 2: Model of Joe with state variables and disturbances [13]

variables in terms of modelling and controller design. The prototype, named “Joe” by its creators, was modelled using modern state space theory instead of the more common classical control, as this allowed for better control of the linear speed and turning rate of the device. But nowadays, there are many investigations on controlling extensions of the one-dimensional inverted pendulum. In which the most challenging problems, investigates is ‘control of a mobile wheeled inverted pendulum system’. The different control methods were proposed to regulate the two-wheeled, inverted pendulum typed robot due to its challenging nature.

In general PID employed for that and there is no need to create mathematical models, but only the choice of the parameters by trial and error method or by experience [14, 15]. Dai F. *et al.* [16] studied friction compensation in two wheeled inverted pendulum. But this research focused on the design and simulation of a two-wheeled, inverted pendulum - A balanced, easy moving vehicle for

the material handling purpose at the congested industrial environments. The mathematical model was simplified significantly by using a fixed weight to simulate the human driver, eliminating many variables. A free body diagram of the system shown in Figure 2.

Variable driver weights, no longer needed to be considered; furthermore, the dynamic loads produced by humans, continuously adjusting the overall system whilst riding “Joe”, could be neglected. This simplification leads to significant differences between the prototype and the final, full scale, rideable device. Numerous plant changes will be introduced to the system when a human driver is used and the prototype may not be sufficiently robust to remain stable under the dynamic conditions. Given the simplified prototype, an accurate model of the device, in terms of forces, could be created. This led to a relatively simple mathematical model that could be used to create the State Space model of the system.

- $f_{dP}$  = Disturbing force at the center of gravity.
- $f_{dRL}$  = Disturbing force on the left wheel.
- $f_{dRR}$  = Disturbing force of right wheel.
- $\theta_d$  = Disturbing angle.
- $CL$  = Torque applied to left wheel.
- $CR$  = Torque applied to right wheel.
- $\delta$  = Yaw angle.
- $x_{RM}$  = Straight line trajectory.
- $\theta_p$  = Pitch angle.

The two areas of interest in terms of control where the pitch and yaw of the device. Pitch control was crucial for the device to remain upright, while the yaw control was needed to control the turning rate. A single input exists in the system and that is the torque applied to the motors and both the pitch control and yaw control require to use of this input to operate effectively. To overcome this problem the system is decoupled, which allows both pitch control and yaw control to operate independently when attempting to meet the linear speed or turning rate commands.

The decoupling of the two systems also improves the designers’ ability to troubleshoot during the simulation and testing phase as two independent systems exists instead of a single interlinked system. As pitch control is far more critical than yaw control because it is controlling the balance of the device, it is given a higher weighting/priority when requiring control of the motors. A rate gyroscope was implemented to measure the angular pitch rate and integrated to give the pitch angle.

Table 1: JOE Inverted pendulum Specification

S.No.	Description of JOE	Specification
1	Height	65 cm.
2	Weight	12. Kg
3	Maximum Speed	1.5m/s or 5.4 Km/h
4	Power Supply	32V, 1.8Ah
5	Run Time	1 Hour

Encoders were mounted on each of the motors to measure the speed of the vehicle. Four LEDs were used to give a visual display of the battery voltage and would turn on in the minutes leading up to complete discharge of the battery and flash upon the batteries reaching their minimal voltage. A summary of “JOE” specifications can be seen in Table 1.

This research aims to

- Analyze state space model in ‘MATLAB’ and also tries to analyze the motor speed.
- Implement a closed loop steering and balancing.
- The next list of goals was to define an extension goal that was an extension of what was hoped to be achieved but were not deemed necessary for success. They included:
- Refinement of the state space model by analyzing real time dynamic data.
- Personalized driving condition by analysis of real time data.
- Regenerative braking/energy system (dependent on the motor controller).

**Modelling and Analysis of Vehicle Frame:** All the components of the vehicles were modeled, assembled and simulated by using CATIA software.

The CATIA diagram for handle bar and motor bracket provided in Figure 3, CATIA diagrams for Clamp, Wheel Boss, handle bar support stem and standing platform were furnished in a Figure 4. CATIA diagrams of base plate, flange and handlebar are shown in Figure 5. CATIA diagrams for battery, handle bar support top and wheel, support bracket and handle bar end cap were shown in Figure 6.

All the parts are not only dependent on the measurements, but also on symmetry and aesthetical look. The material selected is also calibrated in these diagrams using the bill of materials. As symmetry is the main criteria for the auto stabilization of Auto Stabilized Easy Moving Vehicle (ASEMV), it can be seen that all the CATIA parts are symmetrical in nature.

**Finite Element Analysis:** To validate the structural strength of the design of the structural components,

including the base plate, support bracket, boss and flange, a Finite Element Analysis (FEA) is employed by using ANSYS workbench. ANSYS workbench allows a user to import a 3-Dimensional assembled model from many CAD packages.

After applying boundary conditions, material properties and forming an appropriate mesh (to give accurate results and good computational time) results can be obtained in terms of stresses and deflections based on an applied load. The Figure 7 is the model that was used in the FEA. To simplify the model, the motor is reduced to a box with the same cross sectional dimensions. Due to symmetry it is further possible to reduce the model to half the whole assembly.

A fixed boundary condition is applied to the outer cylindrical surface of the boss to simulate a fixed wheel. A load of 1000N is then applied in the vertical direction to the top face of the support bracket. Due to modeling only half the assembly the load experienced is one half of the specified load. However, to account for maximum shock loading (a person jumping on the scooter) twice this load is used (i.e. 100kg = 1000N).

Material properties are then set for each component based on the material they were to be manufactured. By adding the material properties it effectively added to the simulation the weight of all the components. Therefore the total load is the 100kg + weight of components. The results are then obtained for the above conditions. These results, obtained included principle stress, deflection (total and directional) and safety factors for maximum tensile stress and principle stress. The Figure 8 shows the results for equivalent stress showing the safety factor with respect to the yield stress of the material. From Figure 8 one can see that the point of maximum stress is at the output shaft of the motor with a factor of safety as 5. Since the area of maximum stress has a safety factor greater than two for the specified loading conditions, it is concluded that the structural support system is structurally sound.

As a result of the Ben *et al.* [17] project Joe, experiencing deflection of the base plate it seemed appropriate to analyze the maximum deflection of ASEMV. As can be seen in Figure 9 the maximum deflection is approximately 2mm at the middle of the support bracket (The graphical deflection is exaggerated to visually show the way that the model would deform). All deflection is contributed by the deflection of the base plate. It is concluded that a maximum of 2mm deflection was allowable and would not possess a threat to plastic deformation of the base plate, as experienced in the Ben *et al.* [17] project.

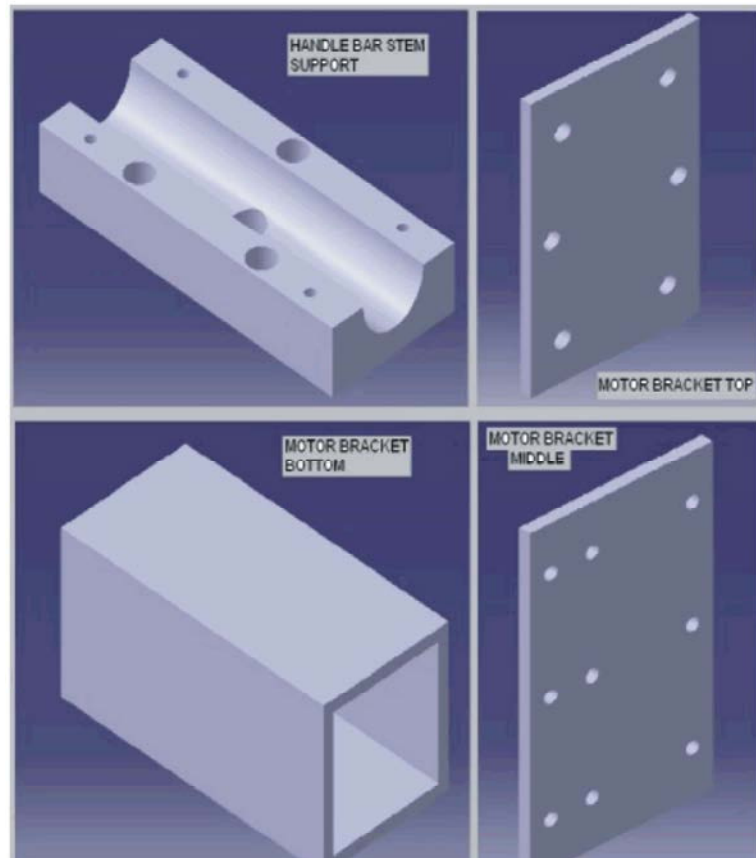


Fig. 3: CATIA diagram for Handle Bar & Motor Bracket

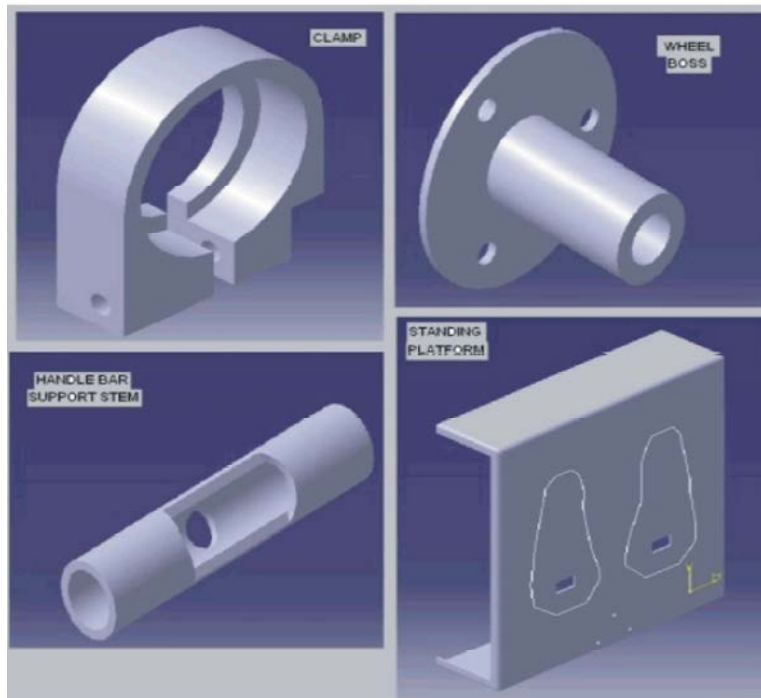


Fig. 4: CATIA diagrams for Clamp, Wheel Boss, Handle Bar Support Stem and Standing Platform

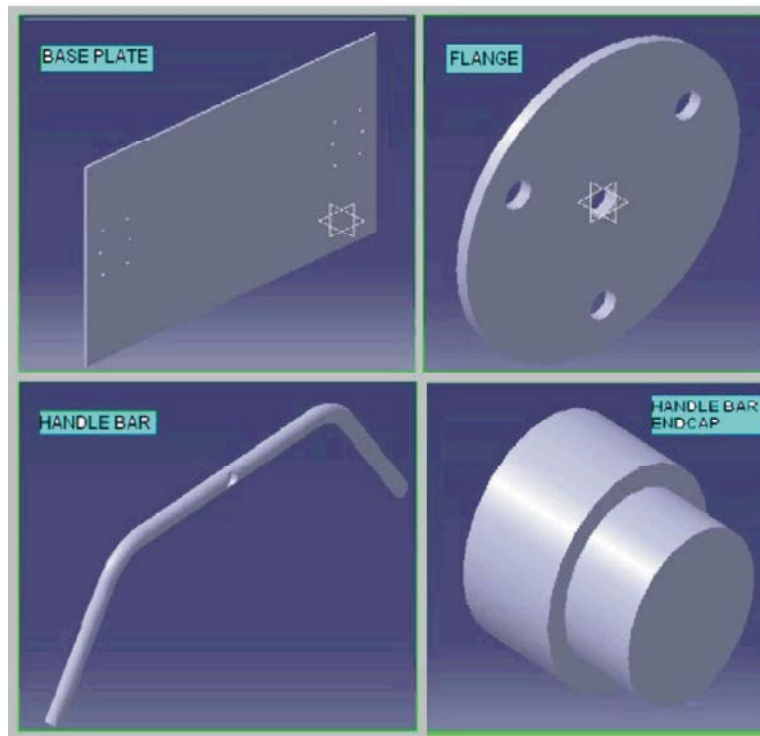


Fig. 5: CATIA diagrams for Base Plate, Flange and Handle Bar

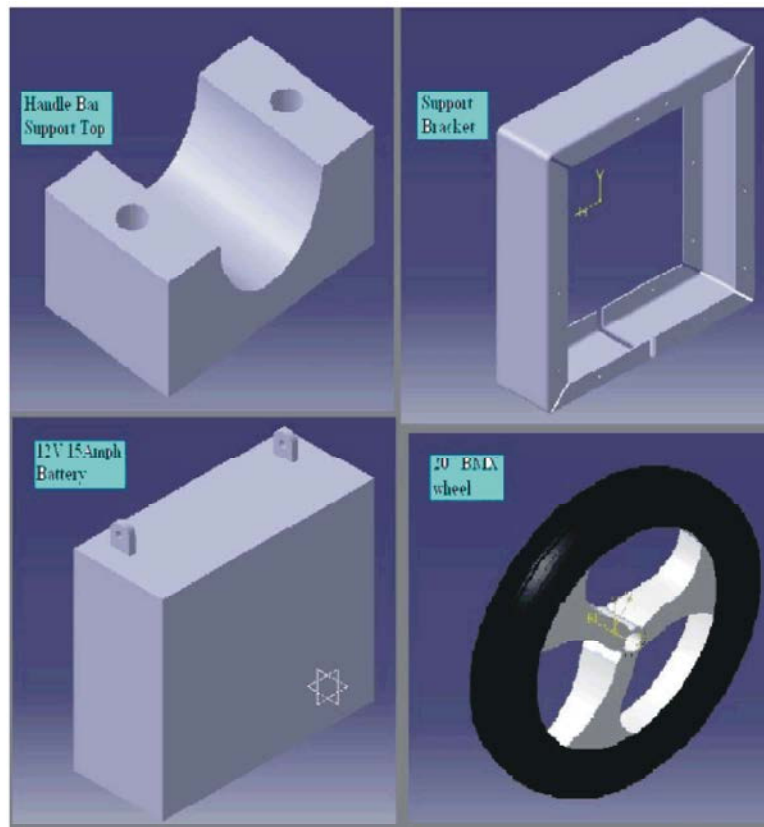


Fig. 6: CATIA diagrams for Support Bracket, Battery, Handle Bar Support top & Wheel & Handle Bar End Cap

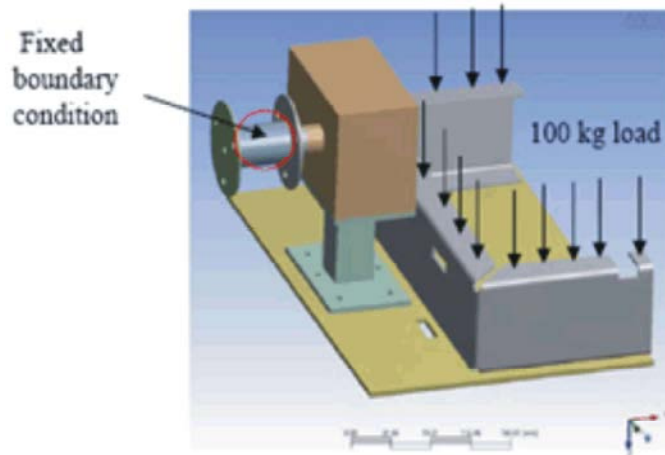


Fig. 7: Model used in FEA

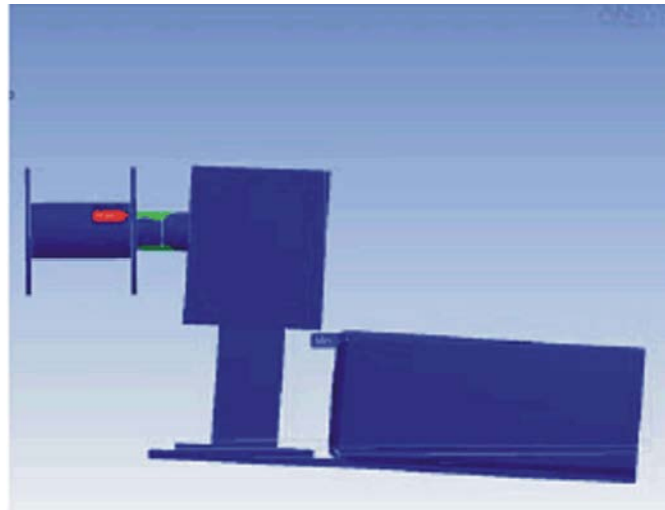


Fig. 8: Safety factor - Equivalent stress

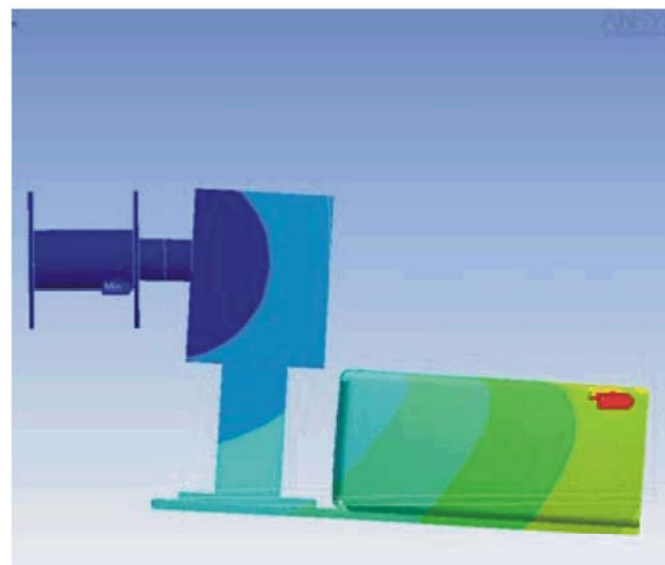


Fig. 9: Total deflection



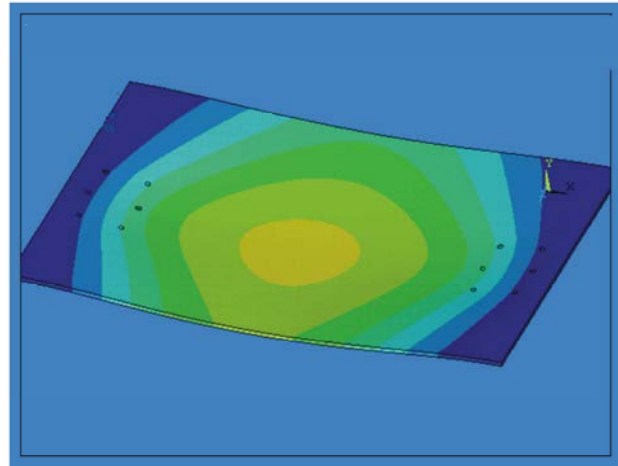


Fig. 10: Total deflections on base plate

It should be noted that this analysis were carried out for simple static loading conditions. During riding, the cast steel output shaft would in fact undergo a cyclic bending force due to rotation which could result in fatigue. It was decided that this would not be a major concern since the equivalent stress is low when compared to the yield stress, such that it should never fail due to fatigue and that the load bearing capacity, as prescribed by the manufacturers, is rated above the applied load. Besides using this entire structure, the finite element analysis is also carried out in separate parts such as in base plate, support bracket. The results are shown in the Figure 10. The Figure 10 shown above is carrying the load of 1400N which is greater than the safety limit of 1200N.

From the results of a simple FEA for both structural strength (equivalent stress safety factor) and deflection it was concluded that structural integrity was more than satisfactory. This enabled the team to go ahead with detailed design with confidence without the need to undertake further iterations on the design of the structural support system.

### Final Assembly and Simulation

**Final Assembly:** The integration of detailed hardware was achieved through the detailed concurrent design of all major components. The use of a three dimensional CAD package, when designing the components outlined and validation through the use of FEA ensured confidence in the final design (Figure 11). The final design has many new and extended features that the original Joe model did not have. These advancements include the design features and advancements which have been outlined in previous sections. This section outlines a brief summary of the features.

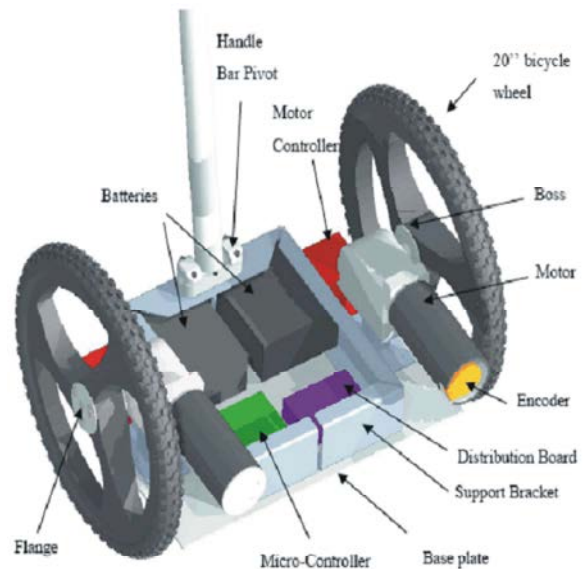


Fig. 11: Final Mechanical system design

The hardware design of ASEMV is a significant feature of the model. Unlike the JOE model, ASEMV is inherently stable without a rider as the center of gravity of the system sits below the axis of rotation. This means ASEMV will not fall over without a rider like the Joe model. Other hardware features include an ergonomic handlebar design which has a multi-point adjusting system, direct drive output from the motors to the wheels and an overall easily adjustable and accessible design.

The shape and positioning of the motors within the vehicle has been converted into a design feature which incorporate the fenders and the rear tail lights. The controller for the vehicle is able to produce stable driving operation for all sorts of riders.

The evolution from standard linear controller to a sliding controller has allowed the vehicle to have an increased maximum velocity while not dramatically affecting the controllability of the device. Another feature of the control is the variable gain with the change in the battery voltage. This allows the vehicle to change the gains of the system as the battery charge depletes to compensate for the loss in power. The control of the vehicle is one of the main features of the device as ASEMv is able to be easily ridden compared to Joe which requires an experienced rider.

The steering of the vehicle is advancement of the Joe model. The close loop steering of the vehicle ensures that the vehicle remains in a straight line when there is no steering input and turns smoothly with a steering input. The steering input is also advancing. The self-centering linear potentiometer is easy to use, uncomplicated and is simply more intuitive for the rider. The electronics of ASEMv have further enhanced the capabilities of the device. The use of breakout boards has reduced untidiness inside the support bracket due to loose wires and created a far easier environment to work in than the messy Joe Davis. The OSMC motor controllers are a far superior device than those used in the Joe model which had a slow serial link speed that affected the performance of the vehicle. The batteries of ASEMv are capable of over one hour of normal operation and have an exceptional charge rate, which allows the batteries to be charged under three hours.

The complementary filter, in conjunction with the gyroscope and the accelerometer, used to measure the pitch angle is a major cost reduction of the vehicle. A Bluetooth can be fitted in the vehicle if the need thus be as it allows for on the fly communication to the vehicle

from a computer. Data can be both uploaded and downloaded to the vehicle which can be used for performance measures and system identification purposes. Although it has not been implemented this year the Bluetooth communication system will enable future work on wireless control. The overall aesthetics of the vehicle is to give a classic yet modern look. The use of a dark metallic green gives a classic feel to the device while the speed stripes on either fender give a sense of speed and power. The metallic finish on the handlebars exudes elegance and sophistication, leaving ASEMv looking a very professional device.

**Simulation of Asemv:** Since the fabrication of ASEMv was not possible due to the lack of availability of spare parts and also importing of them from suppliers, So it was decided to create a virtual reality model of ASEMv. The simulation of the ASEMv was done using CATIA V5 R16.

This simulation was again divided into two categories:

- Simulation along a straight path.
- Simulation along a curved path.

Both the simulations were done using the Digital Mockup module in CATIA V5 R16. The suitable joints were given between the assembled parts of ASEMv and the kinematic and kinetic commands were given for simulating using commands.

**Simulation along a Straight Path:** The Figure 12 shows that the sequence of simulation of the ASEMv along a straight path. When the rider leans forward the drift in the

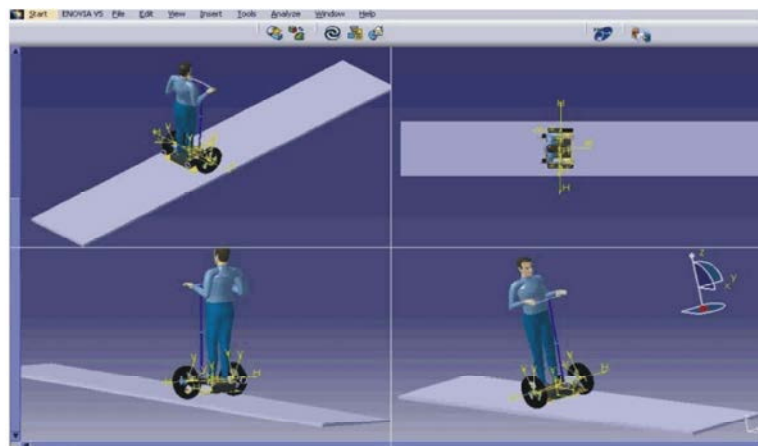


Fig. 12: Diagram for Simulation in straight path





Fig. 13: Diagram for Simulation in curved path

pitch angle is measured by the gyroscope and the further signals are sent to the microcontroller, thereby the vehicle moves forward with acceleration. Similarly for the reverse travel of the vehicle, the rider leans backward and the same set of processes takes place in the vehicle making it move in reverse direction.

**Simulation along a Curved Path:** The Figure 13 illustrates the sequence of the ASEMV along a curved path. When the rider wishes to make a turn, he/she has to slide the self centering potentiometer in the direction of the turn.

It will make, the less flow of current into the wheel along which it has to turn, thus making the wheel act as a pivot. Thus the turning action is achieved while traveling in a curved path.

## CONCLUSION

The aim of this research was to design a coaxial, self balancing vehicle building on the success and short falls of the Ben *et al.* Joe project. A comprehensive literature review was conducted, covering technical information relevant to the project, to form a detailed understanding enabling the development of the best possible prototype. A mathematical model of the system was developed, with and without a rider and successfully implemented within the state space controller. All hardware design, component selection and ergonomics were considered concurrently to minimize mechanical, electrical and rider integration problems and allow the best possible design.

The simulation was done and thus it could be proved that the ASEMV will work when all the procedures are followed to the dot. The mathematical model correlation is another feat that is achieved, which shows that the vehicle can attain stability in all conditions. ASEMV is an easy to ride and reliable device making this project a resounding success.

The outcome of the research can be primarily assessed on the success of achieving the research goals set out at the beginning of this research. The achievement of the primary goals was deemed necessary for the success of the research, whereas the extended goals were considered an extra achievement. All primary research goals have been successfully achieved as well as the completion of some extended goals.

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