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Fabrication and Modelling of Segway

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Abstract

The paper presents the design of a fully functional self balancing vehicle capable of bearing the human load using the principle of dynamic stability. Requirement of the venture includes designing and fabrication of Segway and BLDC motor controller, modeling of the system and implementation of control for stabilization. Indigenous electronic circuitry, accelerometer and BLDC motor controller are used in the system. 500 Watt power motor makes this Segway capable of bearing the human load. It includes static and dynamic analysis of Segway on ANSYS, designing of BLDC Motor controller, mathematical modeling of the system and designing of the PID controller using Root Locus Analysis and implementation on Segway.

Keywords- Segway, BLDC Motor Controller, Inverted Pendulum, PID Control, Kalman Filter

1. Introduction

Segway is a two wheel self balancing vehicle which works on the principle of dynamic stability. It will move forward if the user tilts in forward direction and backward if the user tilts in backward direction.

J. L. C. Miranda stabilizes the self-balancing robot by implementing PID Controller with Kalman filter in order to remove the noise from sensors [1]. A. Ali et al. designed a Segway using 24V permanent-magnet DC motors, implemented PID Controller to balance it. Its motor current rating is 5A and can run for at least 30 minutes with charging time of 12hrs [2]. M. Taylor et al. designed and fabricated a Segway with lower centre of mass and used 9 Volts battery. The system is capable of carrying mass up to 2kgs and line following using three photo-resistors as sensors. The final cost is $120.17 [3]. H. Ha et al. used sensor fusion algorithm between multiple sensors to calculate the real-time angle. They implemented Median filter and EKF (Extended Kalman filter) to reduce the noise of the accelerometer signal [4]. L. Smith et al. made a self-balancing Segway which follow a line and also have mass carrying capability. PID Control is implemented to balance it [5]. W. Zhou designed modelled and controlled the Segway. Project uses two electric scooter motors, two 12V car batteries, Brushed Direct Current (BDC) motor driver (350W 40A), one accelerometer and microprocessors. Modelling of system is also done and PID control is implemented but Segway can move in forward and backward direction only at very low speed and response time is too slow [6]. J. Lam focused on balancing the inverted pendulum by moving a cart in horizontal direction. Non-linear heuristic controller and an energy controller successfully balanced the pendulum from downward to upright position and concluded that Energy controller is faster than the other [7]. K. Mokonop derived the mathematical model (excluding the model of motors), analysed the system model on Matlab and fabricated it. It used belt system, 24 V DC motors (rated speed of 2500 rpm and a rated current of 6A), sensors (accelerometer, gyroscope and inclinometer) and Motorola HC12 microcontroller. According to mathematical modelling it's settling time is 3.5sec for step input and 4sec using feed forward gain method. It was capable of balancing without falling over [8]. M. Tsai and J. Hu used 2 DOF joystick for the balancing of two wheeled cart by implementation of state feedback technique to stabilize it. The electronic differential steering algorithm was find out using real time modelling and verified experimentally [9]. S. Ahmad et al. developed the modular fuzzy control approach for lifting and stabilizing a two-wheeled wheelchair. In the presence of noise and uncertainties, control system is quite robust and managed to stabilize in less than 4sec [10]. K. D. Do and G. Seet designed a control design technique for the elimination of external disturbance by using techniques of the nested saturation and back stepping control design [11]. T. J. Ren et al. applied the neutral-network like self-tuning PID for stability of two-wheeled vehicle. The theoretical and experimentation shows the improvement in system response and have a short recovery time.[12]

This paper introduces fabrication of a Segway using high carbon steel which leads to static and dynamic analysis of Segway to determine its structural durability. Then design of customized BLDC motor controller is discussed which is capable of instantaneous reversal of direction during motion. Finally, system modelling is done with the help of which PID compensator is designed and implemented on the system.

2. Fabrication of Segway

For the fabrication of the vehicle, high carbon steel was chosen over standard aluminum alloys because welding steel proves to be of greater strength and life over aluminum. The tires were procured of the diameter 16 inches with motors fitted within the tire. The size of the hub motors was custom made to fit the tires. The motor model was SXJ-220 DC hub motors. It has a single side shaft out which was connected to the main base via key joint. The handle bar was made of light weight aluminum alloy material and it was hollow for the purpose of wiring. [13]

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The fabricated vehicle has a total weight of approximately 33kgs and placing the electronic components and batteries in an orderly manner allows the vehicle to balance itself out, even when the control system is switched off. Figure 1 shows the fabricated model of Segway.

Fig. 1 Fabricated Segway Vehicle

3. Analysis of Segway on ANSYS

Analysis of Segway is carried out on ANSYS. Materials are assigned i.e. structural steel and neoprene rubber for the main structure and tires respectively and then analysis is done. Static, Explicit Dynamic and Harmonic analysis of Segway are carried out on ANSYS.

3.0.1 Calculations

Weight of cart = 32 kg
Max. Weight of user = Mass x gravitational acceleration
W = 100kg x 9.8 m/s2 = 980N
Pressure on platform (normal) = W= 980 / (0.4*0.4) = 6125 Pa
For acceleration, using equation of motion

$$2 * a * s = V_f^2 - V_i^2 \qquad (1)$$

Suppose the structure halts to 0 velocities. The motor is capable of driving the cart at a velocity of 7.8m/s. So the acceleration turns out to be = 3042mm/s^2 using Equation 1. The BLDC Motor used can allow this velocity with load.

3.1 Static Analysis

Static analysis calculates the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time-varying loads.

3.1.1 Parameters

1. Standard Earth Gravity: 9800 mm/s^2
2. Forces of 20N acting downwards on each handle
3. Mesh size: 50 mm
4. Fixed supports on wheels
5. Pressure on platform = 6125 Pa

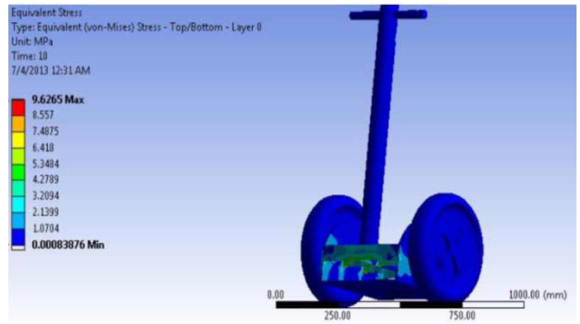

Fig. 2 Static Analysis Result

3.1.2 Results

- Minimum equivalent Von-Mises stress = 8.3876 E -4 MPa (on handle).
- Maximum equivalent Von-Mises Stress = 9.6265 MPa (on platform).
  The result clearly shows that the material can safely withstand the load.

3.2 Explicit Dynamic Analysis

This analysis is used to find out the effects of sudden impact or short duration high pressure loadings on the body. Fig. 3 shows equivalent Von-Mises stresses.

3.2.1 Parameters

1. Acceleration = along Y-axis, -3042 mm/s^2
2. 100 N impact force on handle
3. Velocity of the body along y = -7.7777 m/s
4. Pressure on platform under human load=6125 Pa
5. 200 N force on the front of the platform upon impact (supposed)

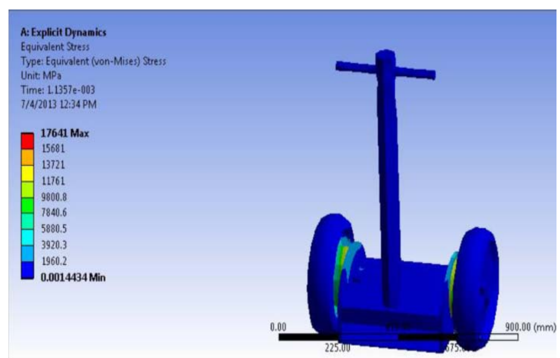

Fig. 3 Equivalent Von-Mises Stresses

3.2.2 Results

- Min. equivalent Von-Mises Stress = 1.4434e-003 MPa (on handle)
- Max. equivalent Von-Mises stress = 17641 MPa (on platform)
  The result shows very high value of stress on the platform, which would damage the structure therefore shock absorbers should be incorporated in the design.

3.3 Harmonic Analysis

Harmonic analysis is performed on a structure to determine the steady-state sinusoidal response to sinusoidal varying loads all acting at a specified frequency.
Fig. 4 and Fig. 5 show equivalent Von-Mises stress and total deformation respectively.

3.3.1 Parameters

1. Acceleration = -3042 mm/s^2
2. Pressure = 6125 Pa normal to the platform
3. Forces on handle = 20N acting downwards
4. Fixed Supports on wheels

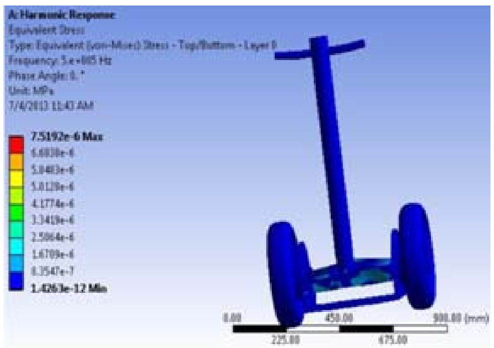

Fig. 4 Von-Mises Stress for Harmonic Response

3.3.2 Results

- Min Stress = 1.4263e-012 MPa
- Max. Stress = 7.5192e-006 MPa
- Reported Frequency = 5e 5 Hz
- Min. deformation = 0 mm on left wheel
- Max. deformation = 9.9629e-9 mm on platform

Surface area of platform under stress = 40 x 40 cm^2
Weight of the user = 80 kg
Force applied through centre of gravity of the platform =800N

Calculations performed on ANSYS Workbench show that:
Stress on the platform (Equivalent Von-Mises stress) = 500000 Pascal i.e. 0.5 MPa. This is less than the yield strength of structural steel, of which the structure is made. So this shows the stability of the structure under the load mentioned above.

This analysis can be performed for both, distributed force and point force methods but as human load will move back and forth therefore distributed force method was preferred.

In three analyses done above, distributed force (pressure) is considered rather than point force. The following figures and results shows that these brought very small change in the result so here assumption of considering the pressure is taken.

Fig. 6 shows the stress present on the platform in case of applied pressure (distributed force) on platform.

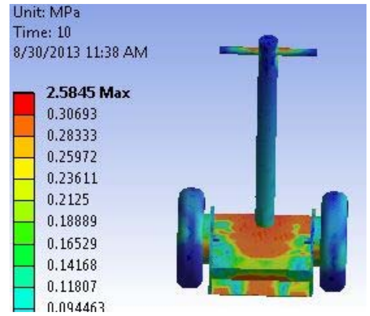

Fig. 6 Stress under distributed force

- Max stress = 2.5845 MPa

This is applied on the complete surface of the platform and acts on all the weak areas so it must have a greater impact than a point force acting through the centre of gravity.

Fig. 7 shows the point force which is applied on Segway, maxim stress and stress distribution when point force is applied.

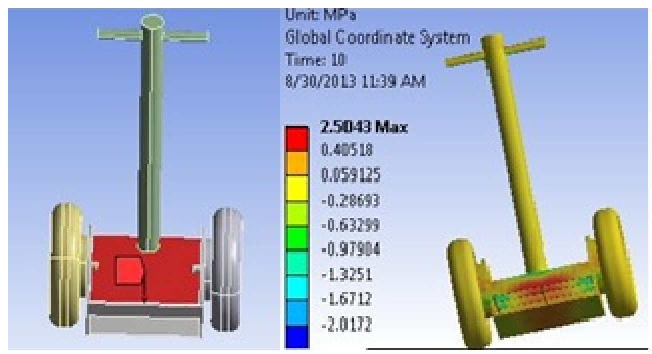

Fig. 7 Point force and stress under its application

- Max. Stress = 2.5043 Pa

The results of stresses as shown in Fig. 6 and Fig. 7 represents that the structure is stable in both case but in the point force case the Equivalent Von-Mises Stress is greater than in the case of distributed force.

4. BLDC Motor Controller

BLDC Motor Controller used in Segway is to control the speed and direction of the BLDC motors like an H-Bridge controls the brushed DC motor. This controller should be capable of doing instantaneous switching of direction depending on the direction of tilting of the Segway.

The BLDC Motors are mostly used for unidirectional purposes where change of direction is of little utility therefore most of the controllers are operated in one direction and cannot change the direction instantaneously without going into free running mode and stopping completely. However in Segway, it is required to frequently change the direction of motion depending upon the tilt position without any delays.

Therefore, it is required to redesign the controller and make a controller which fulfils the requirements. Custom designed BLDC Controller with fast switching solved this problem. BLDC Motor Controller takes input from the hall sensors and the coils are energized according to a specific sequence through an electronic circuitry.

The commutation sequence can be transformed into equations and can be implemented using two different techniques.

1. Using Logic Gates circuitry with 3-phase inverter bridge.
2. Using Micro Controller integrated with 3 phase Inverter Bridge.

4.1 Motor Controller Using Logic Gates

BLDC Motor Controller logic can be implemented using the logic gates circuitry. The logic equations obtained by using the commutation sequence were converted into Boolean Algebraic expressions which were further simplified using K-maps. The equations obtained are:

$$Q1 = (HA \bullet \overline{HB} \bullet D) + (\overline{HA} \bullet HB \bullet \overline{D}) \qquad (2)$$

$$Q2 = (\overline{HA} \bullet HB \bullet D) + (HA \bullet \overline{HB} \bullet \overline{D}) \qquad (3)$$

$$Q3 = (HB \bullet \overline{HC} \bullet D) + (\overline{HB} \bullet HC \bullet \overline{D}) \qquad (4)$$

$$Q4 = (\overline{HB} \bullet HC \bullet D) + (HB \bullet \overline{HC} \bullet \overline{D}) \qquad (5)$$

$$Q5 = (\overline{HA} \bullet HC \bullet D) + (HA \bullet \overline{HC} \bullet \overline{D}) \qquad (6)$$

$$Q6 = (HA \bullet \overline{HC} \bullet D) + (\overline{HA} \bullet HC \bullet \overline{D}) \qquad (7)$$

Q1,Q2 represents transistors input signal for positive and negative sides for A, Q3,Q4 for positive and negative for B and Q5,Q6 for positive and negative for C , D represents direction and HA, HB, HC represents Hall sensor states for windings A,B and C.

4.2 Motor Controller Using Micro controller

The logic circuit increases the size of the circuit therefore it is more advisable to use microcontroller for its implementation. It also enables to make modifications in the program as required.

ATMEGA 16 microcontroller was used and proved to be sufficient for the requirements. The equations were implemented through programming the microcontroller and interfacing it with 3-phase Inverter Bridge. The schematic of the circuit is shown in the Fig. 8.

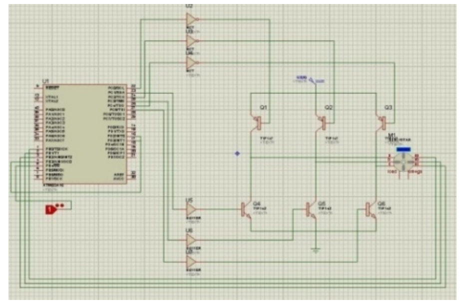

Fig. 8 BLDC Motor Controller (Proteus)

5. Transfer Function

It consists of two parts:

1. Transfer function of BLDC Motor which is between torque and voltage.
2. Transfer function of Segway platform which is between torque and angle.

By combining these two transfer function we will get the complete transfer function between angle and voltage. Both of them are solved separately then they are combined to obtain the overall transfer function of the system.

5.1.1 Theoretical Calculations of Transfer function of BLDC Motor

V = 48 [V], P = 450 [W], I = $\frac{P}{V}$ = 9.375 [A],

With Ref [14],

Rotor Inertia: $J_{rotor} = J_{hub} + J_{shaft}$

J_{rotor} = 2. 1.46 exp -6]

With Ref [15],

$$G(s) = \frac{(s)}{V(s)} = \frac{\frac{1}{Ke}}{\tau m * \tau e * s^2 + \tau m * s + 1} \qquad (8)$$

Approximated as,

$$G(s) = \frac{(s)}{V(s)} = \frac{3.038}{0.6364s+1} \qquad (9)$$

$$G(s) = \frac{\tau(s)}{V(s)} = \frac{\frac{1}{Ke} * m * r * s}{\tau m * s + 1} \qquad (10)$$

$$G(s) = \frac{\tau(s)}{V(s)} = \frac{484.5s}{0.7364 * s + 1} \qquad (11)$$

Equation (9) gives the transfer function of BLDC Motor by relating the angular speed with voltage but we need to convert this angular speed to torque because motor is transferring the torque to the wheel. Therefore, Equation (11) is obtained that is the transfer function of BLDC Motor, using Equation (10) which is relating the voltage and torque of the motor.

5.1.2 Impulse Response of BLDC Motor (Real Time Modelling)

Fig. 9 represents the impulse response of BLDC Motor. Following steps are carried out.

- Plotting of the impulse response.
- Estimation of response using curve fitting tool.
- Determination of unit impulse response.
- Laplace transformation of the expression**.**

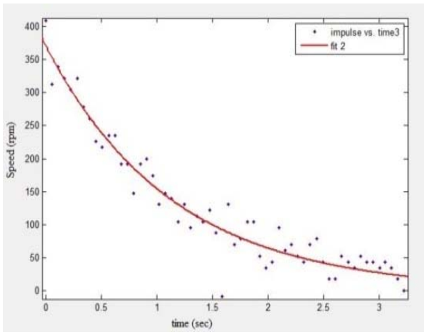

Fig. 9 Impulse Response of BLDC Motor

Transfer function is:

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{3.2788}{s+0.8767} \qquad (12)$$

Due to some assumption considered during the theoretical modelling of BLDC Motor. So the transfer function obtained using real time modelling is more reliable and will be used further.

5.2 Theoretical Calculations of Transfer function of Segway

Segway is modelled keeping the inverted pendulum in mind as shown in Fig. 10.

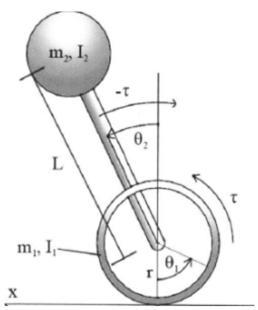

Fig. 10 Inverted Pendulum Model of Segway [16]

With Ref [9],

$$G(s) = \frac{\phi(s)}{\tau(s)} = \frac{(H_1 + H_3)}{[(H_1 * H_2) - (H_3)^2]s^2 - (a)(H_1)} \qquad (13)$$

The general equation for transfer function of Segway is:

$$G(s) = -\frac{(m*r^2 + I_1 + M*L^2 + I_2)}{[(m*r^2+I_1)(M*r*L) - (M*L^2+I_2)^2]s^2 - (M*g*L)(m*r^2+I_1)} \qquad (14)$$

After substituting values in general equation we get:

$$G(s) = \frac{4.046}{0.9777s^2 - 27.72} \qquad (15)$$

Overall transfer function is as follows:

$$G(s) = -\frac{\square(s)}{V(s)} = \frac{1960s}{0.72s^3 + 0.9777s^2 - 20.41s - 27.72} \qquad (16)$$

5.2.1 Impulse Response of Segway (Real Time Modelling)

These responses can be found by taking the data from accelerometer which senses the change in the tilt and then send this data through serial communication to the PC where real time plotting is done.

The impulse response of Segway is used to,

- Show instability of the system.
- Can be used to estimate the transfer function of the Segway by validating the assumptions.

Fig. 11 shows the impulse response of Segway which is also approximated using the “cftool” (Curve Fitting Tool in MATLAB)

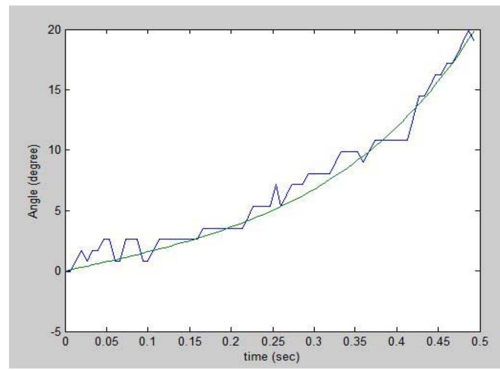

Fig. 11 Approx. Impulse Response of Segway

Transfer Function of Segway is:

$$\text{Seg} = \frac{15.02}{s^2 - 29.08} \qquad (17)$$

The real time analysis validated this transfer function and hence it was further used for the PID calculations.

The final transfer function of the whole system includes the transfer function obtained from real time modelling of BLDC Motor and the transfer function of Segway estimated theoretically.

5.3 Root Locus of the System

Fig. 12 shows the root locus plot of the uncompensated and compensated sytem by implementation of PID compensator.

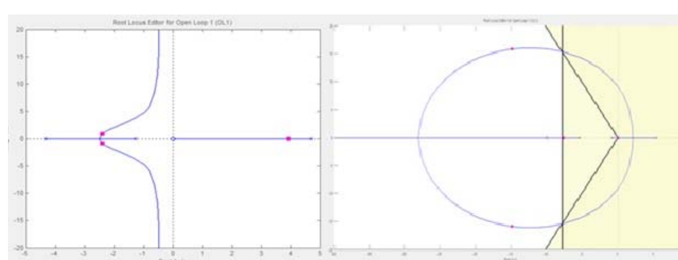
Fig. 12 Root Locus of the system before and after compensation

6. Results

Fig. 13 represents the step response of compensated and uncompensated system which clearly shows that the otherwise unstable system has been stabilized using the PID compensation. The following graph shows that given a unit input the system tends to reach the given set point in a finite time. As the system is a type 0 system therefore there will be a steady state error as shown in the graph.

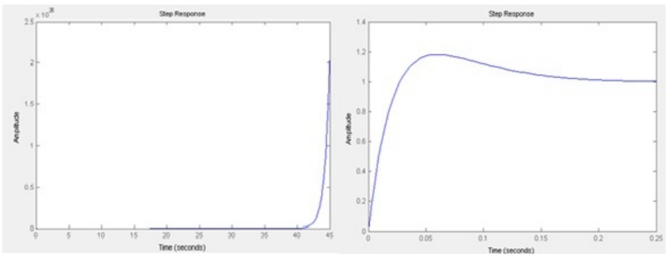

Fig. 13 Step Response of the system before and after compensation

The values obtained for the proportional, integral and derivative constants by analysing the system are then implemented on hardware by coding the algorithm on Atmega-16 in order to completely balance the Segway and for the smooth motion. [17]

Conclusion

The Segway produced is perfectly capable of bearing the human load and is safe in case of any collision or sudden impact. The problem regarding the instantaneous switching of motor controller was solved by redesigned BLDC motor controller. The real time modelling and root locus analysis provided more reliable results as compared to manual tuning. However the ride is not perfectly smooth at the mean position due to jerks and noise in accelerometer data. For that matter it is advised that data obtained from the accelerometer and gyroscope should be filtered using Kalman Filter.

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