Segway Electric Vehicle

Human Transporter

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Abstract — **this paper presents the design, fabrication and control of the Segway human transporter; a two-wheeled, self-balancing electric vehicle. We aim at producing a fully-operational Segway vehicle with a compact design which caters for shock absorption on rough terrains and includes an improved control system. The vehicle has a top speed of 13 km/h, a load capacity of over 2000N and a balancing time of less than 2 seconds.**

Keywords- segway; gyroscope; accelerometer; inverted pendulum; dynamic stabilization; multi-directional shock absorber; PD & PID

I. INTRODUCTION

The original Segway was invented by Dean Kamen from the U.S and released in 2001. The Segway Human Transporter is a self-balancing electric powered vehicle. It is a direct application of one of the most important principles of modern dynamics control system theory and practice, the inverted pendulum (Smith HJT et.al) [1]. The vehicle uses feedback from different sensors and makes decisions regarding changes to control signal to motors that drives it and makes it a closed-loop system (O. Mayr) [2]. Being an inverted pendulum application which utilizes the phenomenon of dynamic balancing, the vehicle controls are based on PD (S. Behnke et.al) [3]. The primary sensor system is an assembly of gyroscopes and accelerometers (N. Yazdi et.al) [4]. Encoders are used to check the direction of motion of the motors. Signals from the gyroscope, accelerometer sensors and encoders are conditioned and fed to the microcontroller (Wilson) [5]. The Segway designed at Grand Valley State University was a miniature prototype, only a few centimeters in height and capable of withstanding a load of only 45N and had a combined motor torque of 3Nm [6]. The Segway soccer robot designed at Carnegie Mellon University also had a limitation of a maximum load capacity of 400N [7]. These vehicles, designed for studying and enhancing the Segway control theory, were built with strict load limitations and were impractical for outdoor testing and usage. The Segway design presented in this paper has no such limitations and is capable to perform in an outdoor environment.

II. MECHANICAL DESIGN

The Segway basically consists of four major elements: the wheel and motor assembly, the sensor system, the circuit board brain and the operator control system. Several mechanical designs have been created on Pro-Engineer and Solid-Works till finally coming up with a compact and effective Segway vehicle structure which includes the use of a multi-directional shock absorber which makes the Segway more effective in the slightly rougher terrains. Each design was run through some standard stress analysis procedures to determine their feasibility and effectiveness. The knowledge from the analysis of each of these designs was used in the creation of the next version of the vehicle design.

The factors taken into consideration during mechanical design were dimensions, weight, materials used for the vehicle fabrication and solving differential equations for inverted pendulum in order to find the state equations for the system. Modeling the system mathematically resulted in providing the equations that were used in MATLAB® to find the optimum compensator constant values for the system. Extending these results, the state equations were also used to calculate the required torque and power to drive the vehicle. These values were used then for the motor selection. The state equations that were found from the mathematical modeling of the system were:

$$\square = \upsilon$$

$$\acute{\upsilon} = \left[\frac{K^2}{R(r^2M_p + J_m + r^2M_w)}\right]\upsilon + \left[\frac{Kr}{R(r^2M_p + J_m + r^2M_w)}\right]V_s$$

$$\square_p = \omega_p$$

$$\square_p = \frac{-g\sin\Theta_p}{\ell^2} + \left[\frac{M_w r}{2M_p\ell^2} - \frac{J_m}{rM_p\ell^2}\right]\acute{\upsilon} + \left[\frac{-K^2\upsilon}{rRM_p\ell^2}\right] + \left[\frac{K}{RM_p\ell^2}\right]V_s$$

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The final vehicle design is presented in this paper as figure 1. It included the use of DC hub motors. The reason for choosing the hub motors was their high power and torque, while their ability to be fixed within the vehicle wheels saving valuable space. This reduced the size of the main platform by approximately 40% as the lower deck platform is no longer needed to accommodate the motors.

Figure 1; design of segway

The shock absorber designed for use on the Segway design is attached between the main frame of the vehicle and the shaft of the DC hub motor. It consists of a single helical spring, coiled and wound around its core in such a fashion that it can absorb a force in virtually all three axes: x, y and z-axes. This small but very effective addition to the Segway design concept provides our Segway design the edge of performing better in the rougher terrains compared to the original Segway. As the shock absorber comes into effect during runs in rougher terrains, this saves the motor shaft from undergoing variable loads and fatigue; as the major portion of the shock impact produced due to the terrain is absorbed by the shock absorber.

III. FINITE ELEMENT ANALYSIS

Finite Element Analysis is an important step required for the study of the structure design. The aim of analysis is to determine whether the structure behaves as desired under the prescribed loading. The software used for analysis includes Pro-Engineer for static and modal analysis while for dynamic analysis ANSYS and Solid Works were used since solid works has its own physics engine. Multiple designs were made and analysis of each design was performed. The optimum design was then selected based on the results from the analysis. The center of mass of the Segway was kept as low as possible in order to improve the vehicle stability. Figure 2 below shows the static analysis of the final design carried out on Pro-Engineer

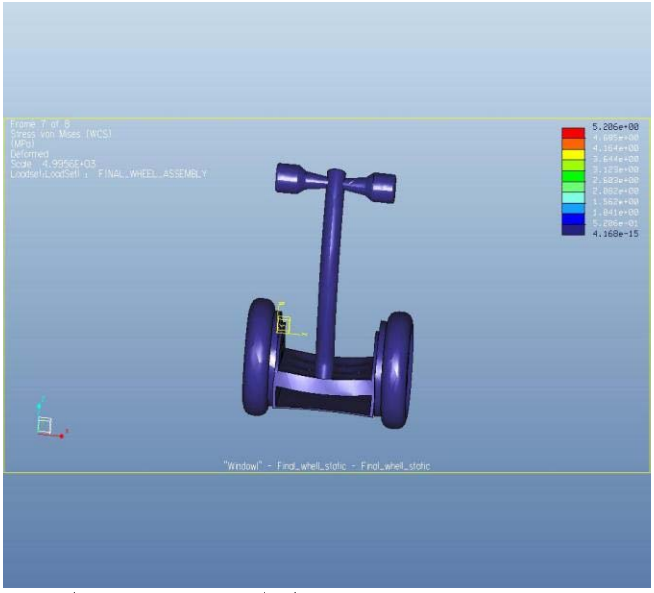

Figure 2; stress analysis

The graph for the maximum vehicle material and structure deflection when a load of up to 2000N is applied is shown in figure 3.

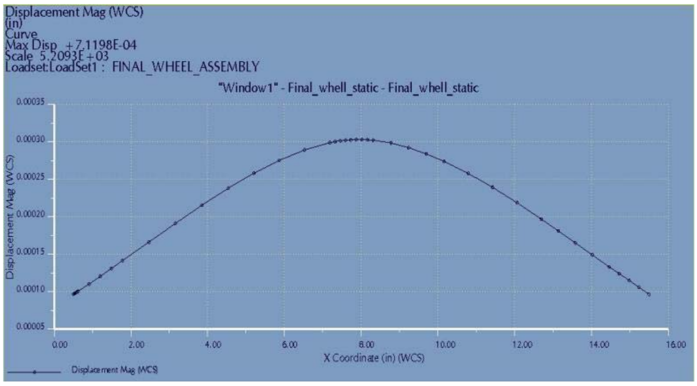

Figure 3; stress distribution of base

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The first step in analyzing a design on Ansys is meshing. The meshes were kept smooth for the main base of the vehicle. The mesh size was kept with a relevance of 2 for the base. Octagonal meshes were selected and the features of curve smoothing were kept on. The meshes on the main base were closer and smaller by a factor of two compared to the ones on the tires and the shaft. Smaller meshes mean a more detailed and sensitive analysis of the deformations and stresses experienced by the structure. Since the base was the object of interest for the analysis of loads, the meshes were kept smaller for the analysis of this part. The handle and rod of the Segway were suppressed as under normal conditions, no load is being applied on them and so they can be ignored for the analysis. The shaft is protected by the shaft mount, as the hub motor shaft does not rotate and requires a mount to be made for it to be fixed in, so the shaft does not experience an extreme deformation or load. Thus, this leaves us with the most important part of the design that needs an analysis to be carried out on, which is the vehicle base. Once the meshing was complete, simulation of the analysis was carried out on the vehicle design. The analysis of the total deformation of the vehicle under an extreme case load of 1500N distributed over the platform is shown in figure 4 below.

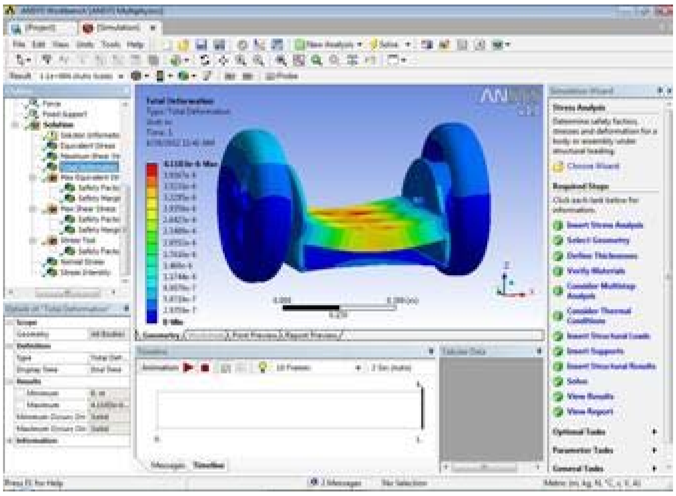

Figure 4; stress analysis

Modal analysis was done to see the structural behavior of the vehicle design under excitation forces of different frequencies and to locate any resonance and see if the structure fractures or fails at these natural frequencies. The modal analysis results of the base structure, with tires and shafts of the motor attached at a frequency of 1078 Hz, shows the deformations in the structure at the first resonating frequency, which is the 5th frequency mode. The second resonance occurs at a frequency of 1135 Hz. This is the 6^{th} frequency mode for the vehicle base structure. Note that these results are carried out after suppressing the handle and rod attached to the vehicle but keeping the tires and the shafts of the vehicle attached.

These results show the maximum bending in the vehicle structure that may occur at the natural frequencies, when resonance occurs. The third result shown is at 2048 Hz. It shows the bending of the vehicle at the 11th mode showing that resonance does not occur again for the first 12 modes except for has been shown earlier. Note that at higher frequencies, there are chances that resonance may occur again but 12 modes are a comprehensive evaluation of the resonance detection and it occurs twice for the first 12 modes. The result at 2048 Hz is shown below in figure 5.

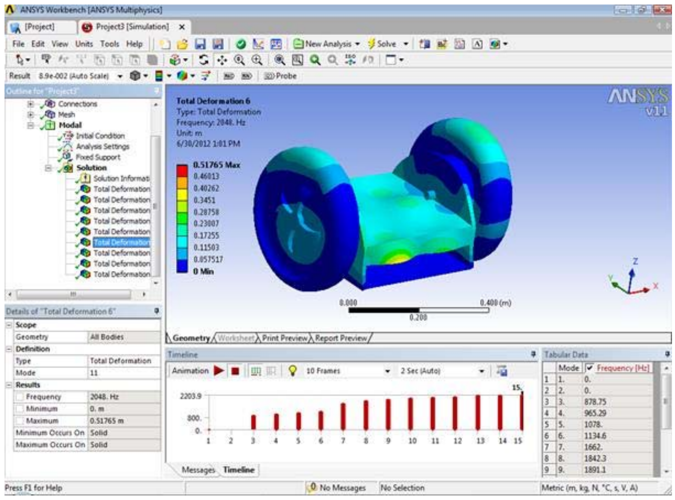

Figure 5; Stress analysis on second design

IV. FABRICATION

For the fabrication of the vehicle, high carbon steel was chosen over standard aluminum alloys. This was done on the basis of the fact that welding was required for the manufacturing of the base and welding on steel proves to be of greater strength and life over aluminum. 16inch diameter of the wheels was chosen. The hub motors procured were 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 base via key joint. The handle bar was made of plastic material and it was left hollow for the purpose of wiring to the control panel on the handle bar from the main system electronics underneath the base platform.

V. BLDC MOTOR AND CONTROLLER

As already mentioned, we chose BLDC Hub motors for use on the Segway. Motor had following specifications: 48V rated voltage, 1000W rated power, 500 rpm rated rotating speed, 83% rated efficiency and 13.5Nm rated torque. BLDC motors offered the advantage of having no brushes needed for commutation since commutation is done electronically, and hence they require less maintenance. This also results in higher speed ranges.

In addition to this, BLDC motors offer better speed versus torque characteristics, high dynamic response, high efficiency, longer operating life and noiseless operation. Also, the torque to weight and size ratios are higher which makes BLDC motors useful in applications where space and weight are critical factors. (Padmaraja Yedamale) [8]

Brushless DC motor controllers were purchased for driving the motors. Figure 6 below, shows the BLDC motor controller with its wiring specifications.

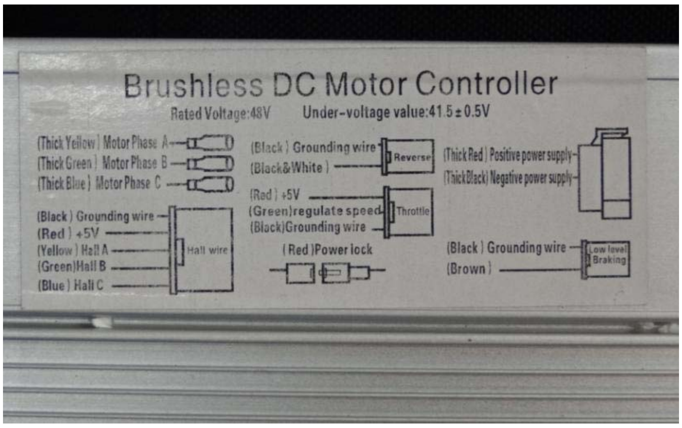

Figure 6; BLDC motor controller

After acquiring the motor and its controller, the first step is to determine the connections of motor with its controller. Just because the colors of motor wires and the motor controller wires match, it does not mean that they will match correctly. Hence it is very important to determine the right connections before full power is applied to the controller, since wrong connections can easily destroy the motor, controller or both. [9]To determine the right connections, following procedure was carried out:

- Connect controller throttle wires (3 thin wires - B,R,G) to (5v hall sensor) throttle.
- Connect controller hall sensors (5 thin wires - B,R,G,Y,BL) to motor hall sensor wires.
- Connect controller phase wires (3 thick wires - G,Y,BL) to the motor phase wires.
- Connect controller negative wire (thick black wire) to power supply negative (-).
- Connect controller main power positive (thick red wire) to (2 amp fuse) power supply positive (+).
- Connect controller ignition positive (thin red wire) also to (2 amp fuse) power supply positive (+).
- Slowly twist throttle and observe motor rotation. Make a spreadsheet to record the observed results.
- If no motor rotation occurs, leave the hall wires the same and switch two phase wires as shown in spreadsheet.
- Again, slowly twist throttle and observe motor rotation. Use spreadsheet to record motor observations.
- If no motor rotation occurs, again repeat the above step with the next possible phase wires combination.

Where B=black, R= red, G =green, Y = yellow and BL = blue. Controller should be tested with the motor at "no load" (motor/wheel off the ground and free to spin easily). All the thirty-six combinations may need to be tried in order to determine the right connections. If a wiring combination produces a "smooth" rotation in the "forward" direction this means testing is complete and that configuration can be kept. If the smooth rotation occurs in the "backward" direction then switch 2 hall wires, and try the six possible phase wire combinations with these hall wires configuration. Most of the Hall/Phase wire combinations produce no rotation at all and some combinations produce "rough" rotation in either the forward or reverse directions. A correct Hall/Phase wire combination runs very smoothly and draws very little current (1 or 2 amps) under no-load testing. A wrong Hall/Phase wire combination will generally run very rough and draw much higher current under no-load testing. Using the wrong wiring combination under a full load for example on the road, can and will damage the controller and/ or the motor. (Padmaraja Yedamale) [8]

VI. ELECTRONICS

Sensor system of the Segway consists of an assembly of accelerometers and gyroscopes. They are used to determine the change in tilt of the vehicle. Gyroscopes are used in addition to accelerometers to enable smooth balancing and reduce the vibrations/oscillations caused when using accelerometer only. The optimum range for the working of the accelerometer was from 2.7 to 3.6V. We opted to operate the accelerometer at 3V. Since the power distribution circuit board provides constant 5V power outlets, accelerometer board is designed in such a way so that voltage is dropped through the diodes to achieve 3V, which is then fed to the accelerometer chip. (Ron Goldman) [10].The accelerometer chosen is shown in figure 7.

Figure 7, Accelerometer

The gyroscope chosen for the vehicle was LPR 550AL, shown in figure 8. It enabled the integration of Signal conditioning circuitry and multi-axis integration. (Steven Nasiri) [11]

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Figure 8, Gyroscope

AVR AT-Mega 16 microcontroller was used for controlling the vehicle. The main advantage of using this controller is that it comes with built in Analog to Digital converter and PWM function both of these are very useful for our project as the gyroscope and accelerometer give analog output which needs to be digitized before it can be processed by the controller. The PWM function is used in controlling the wheel motors. [14] For the Segway control, the controller gets its input from the gyroscope and accelerometer sensors and then calculates the speed and direction of motors in order to maintain balance. The controller board was designed to provide all the required inputs and outputs for the sensors and the motors.

VII. CONTROLS

For balancing itself, the vehicle utilizes the data from the accelerometers and gyroscopes, which is fed to microcontroller. The controller first digitizes the analogue data from the accelerometer. It gives 8 bit digital value based on the analogue value from the accelerometer. Simultaneously the gyroscope output is processed. The combined data is used to calculate the exact orientation and the rate of tilt of the vehicle. The data is then used to decide the direction of wheel motion and speed required to prevent the vehicle from falling thus bringing it back to its mean position. The control scheme implemented is Proportional-Integral-Derivative controller. It gives the 0-100% output based on a specified range of the tilt of the vehicle in both directions.

The sequence of the working for balancing the vehicle is as follows: first the direction of tilt is computed by comparing the accelerometer and gyroscope outputs with the reference values for each. The reference value of each sensor is different and it is basically the value each sensor gives when the vehicle is at its mean position and stationary. The value of the sensors decreases when the vehicle tilts in one direction and increases when the tilt is in the other direction. The direction of tilt is calculated by comparing the current value of the sensors with their reference value. The main control logic is also shown in flow-chart (figure 9).

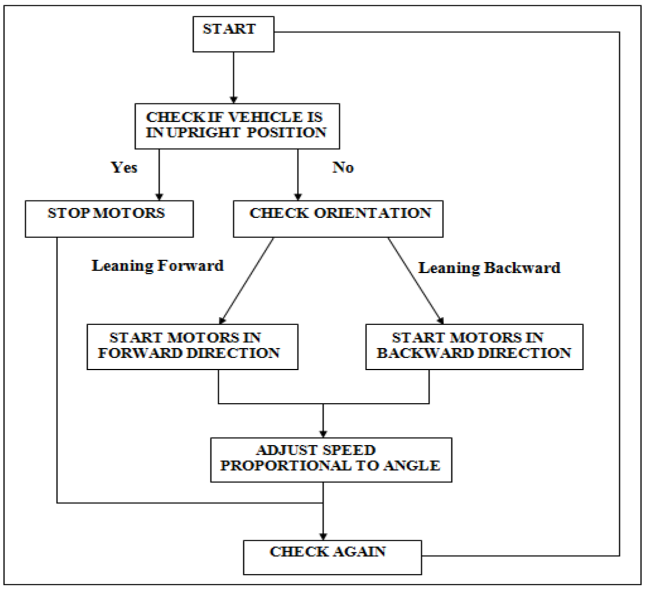

Figure 9; flow chart of sotware

To maintain the balance, an appropriate torque has to be applied by the motors on the wheels that is just sufficient to maintain the balance and bring the vehicle back to its mean position when it is displaced and hence preventing it from falling. The torque of motors is varied by changing the voltage at the throttle pin. To vary the voltage we used DAC. The microcontroller controlled the digital input to DAC which resulted in varying DC voltage at its output. The two different formulas are used depending on orientation of vehicle (that is whether the value of accelerometer is greater or less than the reference value).

The registers in the microcontroller accept 8-bit values only. So the percentage calculated for the duty cycle is converted to a scale of 0-255(8bit) and this value is used to generate the signal for DAC.

The signal for direction and speed of motors is then generated according to the calculated values and then it is sent to the motor controllers. The vehicle control utilizes the Proportional – Integral - Derivative (PID) algorithm which helps in reducing the magnitude of overshoot; hence it helps in smoother operation. The PID controller uses sum of the proportional, integral and the derivative terms to calculate the output of the controller.

This feedback control provides for a more accurate and fast balance of dynamic systems.(John A. Shaw) [16] The state equations found from the mathematical modeling of the vehicle were used in MATLAB to calculate the optimum compensation constant values for the controller. This helps in a very smooth operation of the vehicle and provides a more comfortable and reliable drive for the user.

Another notable thing when the vehicle is stationary is that Proportional-Integral-Derivative (PID) control is being used. In the PID control, the proportional, integral, and derivative terms are summed to calculate the output of the PID controller. This allows for a smoother and a more reliable balance of the vehicle when it is stationery. This ensures that the working of the vehicle is most comfortable for the user and enhances the user's vehicle drive experience. (Tim Wescott) [16]

VIII. CONCLUSION

The Aim of this research was achieved by designing, manufacturing and controlling a two-wheeled self balancing Segway vehicle. Improvements were made to the existing Segway designs by using the multi-directional shock absorbers between the vehicle motors and the main user platform, allowing for a better drive in rougher terrains for the vehicle without the shaft undergoing a large stress load.

The vehicle control was also modified by using PID feedback control. The PID controller is implemented when the vehicle is moving. PID controller, when vehicle is stationery, also ensures the smooth balancing of the vehicle. Successful design implementation and fabrication of the vehicle was achieved and the modified control strategy was implemented for the smooth running of the vehicle.

IX. ACKNOWLEDGEMENTS

This research could not have been completed without the endless support of the Department of Mechatronics Engineering, College of E&ME, National University of Sciences and Technology, Pakistan.

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