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Development of a Segway like Two wheel self-balancing robot

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Abstract

The Segway is an intelligent vehicle which uses gyroscopic sensors to detect the motion of rider as like as two wheeled self-balancing robot, so that he can accelerate, brake or steer the vehicle. The inverted pendulum principle provides the mathematical modelling of the naturally unstable system. This principle is utilized to develop and implement a suitable stability control system that is responsive, timely and successful in achieving this objective. The microprocessor processed the feedback signal using a PID algorithm to generate position control signals i.e. apply proportional force to the motors as given by the program logic in order to restore the balance or to bring it back to its original vertical position. The control algorithm is implemented using C-programming. An android app is used for the direction of two wheel self-balancing robot. The opportunity to calibrate and perform additional fine tuning of the design is also explored.

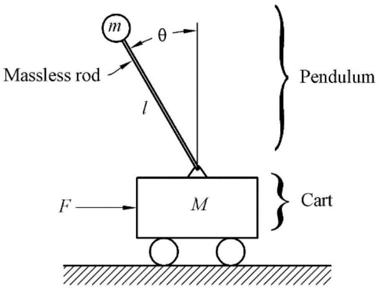
Keywords: Segway, Self balancing, Feedback control, Robot

1. Introduction

In the field of transportation various companies of the world are trying hard to put more work into building environmentally friendly vehicles than ever. Tremendous air pollution, global warming and the need for sustainable energy pushes the demands for efficient, green energy powered vehicles. The main purpose of this work is 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. This is why a prototype of this Segway type vehicle has been designed and constructed. There are many scopes regarding this work. Since there are traffic jam issues in our country, this prototype helps to raise the awareness of developing this type of vehicle in future. The developed algorithm can be used to build one wheel self-balancing vehicle in future and add extra features if improvement is needed. The system can only be used for a single person but not for heavy loads or carry many passengers. Various works have been done which are related with this topic. A self balancing scooter has been developed that functions similarly to the Segway Human Transporter (HT). In this system, angular feedback from a gyroscopic sensor and PWM output to motors are used in a control system to achieve balance of EDGAR [1]. Two wheeled balancing robots are an area of research that may well provide the future locomotion for everyday robots. The unique stability control that is required to keep the robot upright differentiates it from traditional forms of robotics. The inverted pendulum [2] principle provides the mathematical modelling of the naturally unstable system. This is then utilized to develop and implement a suitable stability control system that is responsive, timely and successful in achieving this objective [2]. There is a need for smaller and more economic transportation systems. Personal transporters have made their way as consumer products to address this need. They can be found in two, three or 4-wheeled configuration. The two-wheeled configuration is a two-wheeled inverted pendulum system. One example of a commercial two wheeled transporter is the Segway Human Transporter [3]. The Segway Personal Transporter 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. This is prevented by electronics sensing the pitch angle and its time derivative, controlling the motors to keep the vehicle balancing. This kind of vehicle is interesting since it contains a lot of technology relevant to an environmentally friendly and energy efficient transportation industry. [4]. Two wheel self-balanced vehicle has been designed where two heavy rotating disks were used with hub motors at the chassis to compensate the tilt of the vehicle and get it stabilized. An android device is used to measure the tilt angle of the chassis using orientation sensor. The data then is sent to a Bluetooth receiver that is connected with an Arduino. An android application is developed which takes the angle of tilt of the vehicle as data input from the phone and sends a control signal to the Arduino accordingly [5]. A self-balancing platform which are named as Segway has been developed which help to promote a modal transfer away from the automobile for short-distance trips Electric scooters and Segways are two, user friendly, in modes of transportation that facilitate effortless travel and could provide suitable transportation in metro cities [6]. Two wheel self-balancing vehicle has been developed using Arduino. Tilt angle and motor speed rate are functioning as input of the system to perform balancing of the vehicle. Inertia Measurement Unit (I.M.U.) and DC motors were used as sensor and actuator respectively for this system. Moreover, the control of vehicle system used PID controller and implemented in Arduino board [7].

2. Methodology

The underlying principle of developing two wheel self balancing robot is to solve the control dynamics of inverted pendulum problem. Arguably the most prevalent example of an inverted pendulum is a human being. A person with an upright body needs to make adjustments constantly to maintain balance whether standing, walking, or running. Therefore, if self balancing is possible then it can carry person for transportation when standing on it. The system prototypes are inverted pendulum on a cart and a self-balancing two wheel vehicle. Firstly, the systems are briefly described, then the equations of motion are derived and mathematical modeling is done, then the design of the controller, simulation of the controlled model and finally prototype response is approached. This system is shown in Figure 2.1. The cart is free to move horizontally. The rod is connected to the cart through a rotational pin joint.



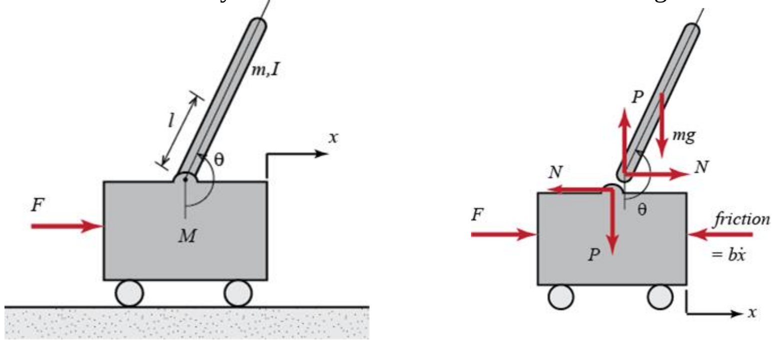


Fig. 2.1 (a) Cart pendulum system **Fig. 2.2** (a) Schematic diagram (b) Free body diagram system dynamics

This system is in unstable equilibrium when the rod is standing upright. Mathematically, this equilibrium can be maintained as long as there are no input forces whatsoever on the system. However, such conditions do not exist in real systems and some means of stabilization is needed to maintain the pendulum in the upright position. A force *F* must be applied to the cart in order to move the cart pivot back and forth from one side of the pendulum mass center to the other side. The pendulum is always falling over, but the cart motion tries to keep the leaning angle, μ, at a small level. The control scheme used is a Linear Quadratic Regulator (LQR) for state-feedback control. The LQR is setup to drive the tilt angle to zero. We used as a benchmark for testing control algorithms (PID controllers, state space representation, neural networks, fuzzy control, genetic algorithms, etc.).It has some characteristics like; instability, multivariable and non-linearity. The control algorithm is implemented using C-programming. The microprocessor processed the feedback using a PID algorithm to generate position control signals i.e. apply proportional force to the motors as given by the program logic in order to restore the balance or to bring it back to its original vertical position.

Mathematical Modeling

In this case a two-dimensional problem is considered, where the pendulum is constrained to move in the vertical plane shown in the figure 2.2. For this system, the control input is the force *F* that moves the cart horizontally and the outputs are the angular position of the pendulum μ and the horizontal position of the cart *x*.
Summing the forces in the free-body diagram of the cart in the horizontal direction, the following equation of the motion is obtained:

$$M\ddot{x} + b\dot{x} + N = F \tag{1}$$

Summing the forces in the free-body diagram of the pendulum in the horizontal direction yields the following expression for the reaction force *N*.

$$N = m\ddot{x} + ml\ddot{\theta}cos\theta - ml\dot{\theta}^2 sin\theta \tag{2}$$

Combining these two equations the first governing equation becomes

$$(M + m)\ddot{x} + b\dot{x} + ml\ddot{\theta}cos\theta - ml\dot{\theta}^2 sin\theta = F \tag{3}$$

Summing the forces perpendicular to the pendulum

$$Psin\theta + N\,cos\theta - mgsin\theta = ml\ddot{\theta} + m\ddot{x}cos\theta \tag{4}$$

Summing the moments about the centroid of the pendulum yields

$$-Plsin\theta - Nlcos\theta = I\ddot{\theta} \tag{5}$$

Combining these last two expressions, the second governing equation becomes

$$(I + ml^2)\ddot{\theta} + mglsin\theta = -ml\ddot{x}cos\theta \tag{6}$$

Since this system is considered as linear, linearization of the equations are necessary. Specifically the equations should be linearized about the vertically upward equilibrium position, θ =π and will be assumed that the system stays within a small neighborhood of this equilibrium. This assumption should be reasonably valid since under control the pendulum should not deviate more than 20 degrees from the vertically upward position. Let φ represent the deviation of the pendulum's position from equilibrium, that is, θ = + φ.

Again presuming a small deviation (φ) from equilibrium, we can use the following small angle approximations of the nonlinear functions in our system equations:

$$cos\theta = \cos(\pi + \varphi) = -1 \tag{7}$$

$$sin\theta = \sin(\pi + \varphi) = -\varphi \tag{8}$$

$$\theta^2 = \varphi^2 = 0 \tag{9}$$

After substituting the above approximations into non-linear governing equations, two linearized equations of motion is obtained [6]

$$(I + ml^2)\ddot{\varphi} - mgl\varphi = ml\ddot{x} \tag{10}$$

$$(M + m)\ddot{x} + b\dot{x} - ml\varphi = F \tag{11}$$

To utilize this equations for control, transfer function needs to be formalized. Therefore taking Laplace Transformations assuming zero initial conditions in equation (10) and (11), the following equations are obtained:

$$(I + ml^2)\varphi(s)s^2 - mgl\varphi(s) = mlX(s)s^2 \tag{12}$$

$$(M + m)X(s)s^2 + bX(s) - ml\varphi(s)s^2 = F(s) \tag{13}$$

To find first transfer function for the output φ(s) and an input of U(s), X(s) need to be eliminated from the above equations. Solving the first equation for X(s)

$$X(s) = [\frac{I+ml^2}{ml} - \frac{g}{s^2}]\varphi(s) \tag{14}$$

Substituting in Eq.13 we have $(M + m)\left[\frac{I+ml^2}{ml} - \frac{g}{s^2}\right]\varphi(s)s^2 + bX(s) - ml\varphi(s)s^2 = F(s)$ (15)

Rearranging, the transfer function becomes $$\frac{\varphi(s)}{F(s)} = \frac{\frac{ml}{q}s}{s^4 + \frac{b(I+ml^2)}{q}s^3 - \frac{(M+m)mgl}{q}s^2 - \frac{bmgl}{q}s} \tag{16}$$

Where, $$q = [(M + m)(I + ml^2) - (ml^2)] \tag{17}$$

From the transfer function above it can be seen that there is both a pole and a zero at the origin. These can be canceled and the transfer function becomes the following

$$\frac{\varphi(s)}{F(s)} = \frac{\frac{mls}{q}}{s^3 + \frac{b(I+ml^2)s^2}{q} - \frac{(M+m)mgls}{q} - \frac{bmgl}{q}} \tag{18}$$

3. Components Used

The components used in this system are Arduino MEGA, Motor driver: tb6612fng, Voltage regulator 7805 for 5V, Shield for Arduino, Gyro + accelerometer sensor MPU 6050, Bluetooth module HC05, Lipo battery 12V, Buzzer for debugging, Capacitor and Resistor 220 ohm for LED.

4. Sensing System

It is based on the theory of Classis Inverted Pendulum problem. To achieve the objective, two things are done like angle of inclinations (Roll) is measured and to maintain the vehicle vertical by making zero angle, motors are controlled for going forward and backward. Forces of gravity is measured by accelerometer to obtain the angle of robot though lot of error and noise is also found as rest of the forces are also measured. Angular velocity is measured by gyro sensor and after integrating the data angle of robot is obtained. But the measurement is not perfect and deviation is found, in short time it is good but for long time angle is deviated and drifted along with time. For this reason, sensor fusion is introduced like Kalman filters and Complementary filters as shown in Figure 4.1 and Figure 4.2.

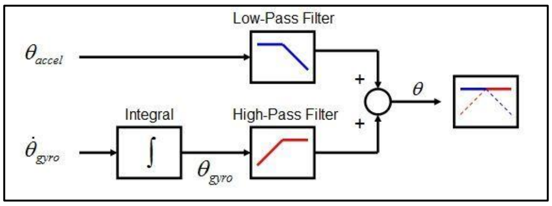


Fig. 4.1 Sensor fusion accelerometer gyroscope

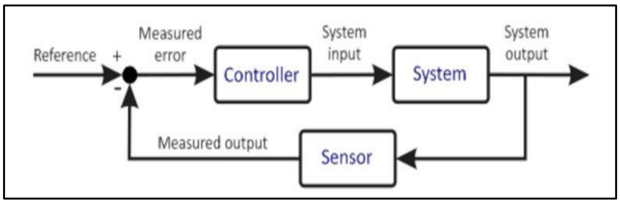


Fig. 4.2 PID controller design

The deviation from upright position is measured by the sensor MPU6050. As deviation is increased, it eventually causes "center of gravity (COG)" to move outside the limits of baseline, causing tip over. To prevent tipping over, depending on deviation observed, the baseline is quickly moved to get directly under the new position of COG. In this robot motors are used to bring wheels directly under this position. MPU6050 communicates to Arduino through I2C protocol. It provides measurement of acceleration in G forces, in 3 axes and angular velocity in deg/sec in 3 axes. The sensor circuit is shown in figure 4.3

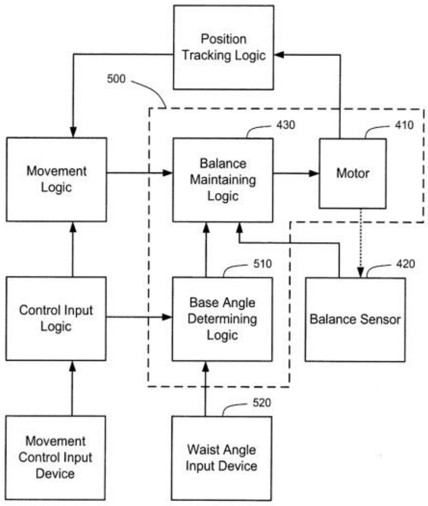
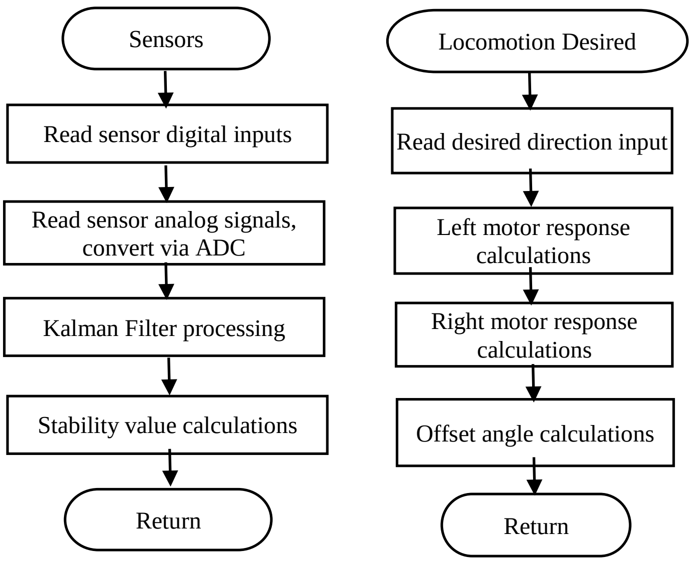


Fig. 4.3 Sensor circuit

5. Control system design

We have derived the dynamical model of an inverted pendulum, then linearized it around the stable operating point. With this simplified model we have found the LQR controller which keeps our robot upright and tracks desired linear and angular velocities. The flowcharts for sensors, locomotion and balancing are shown in Fig. 5.1 and Fig. 5.2.



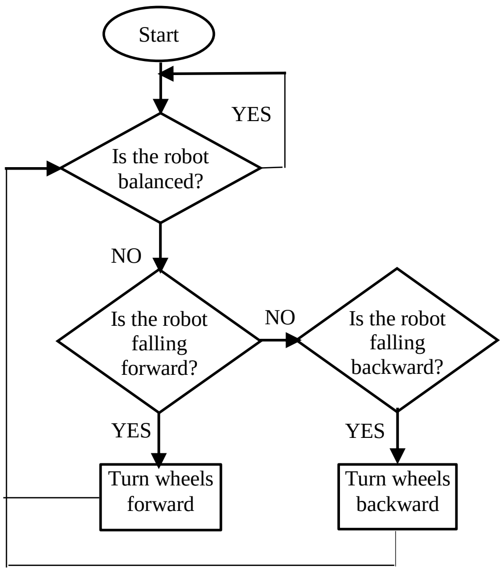


Fig. 5.1 Sensors and locomotion desired sub-routine flowcharts

Fig. 5.2 Self balancing flowchart

Tuning of PID controller to minimize the error, will balance the two wheel robot. The control scheme is shown in fig. 5.3. The terms are as usual for the PID controller. The output from the robot is fed back to the controller through gyro-sensor which senses the orientation of the robot. The PID controller uses this signal and computes the desired response to the motor controller. The motor controller controls the both motors based on the PWM (Pulse Width Modulation).

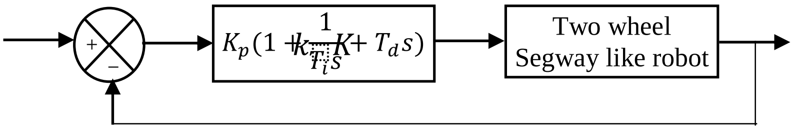


Fig. 5.3 PID Controller for two wheel Segway like robot

6. Mechanical System Design

The mechanical system is designed based on the analysis of the following free body diagram of wheel of the robot shown in figure 6.1. The complete setup of the two wheel Segway like robot is shown in figure 6.2.

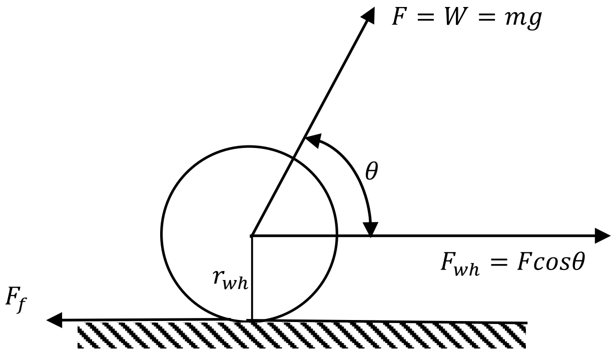


Fig. 6.1 Free body of the wheel

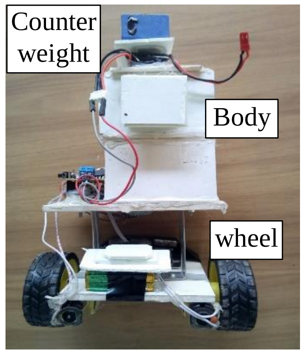


Fig. 6.2 Proposed Model of Segway like robot

Design of wheel torque, $T = F_{wh} \times r_{wh}$ (19)

Here, F_{wh} = Net horizontal force of a wheel (left or right), r_{wh} = Radius of the wheel

$$F_{wh} = F/2 \quad (20)$$

F = Horizontal force acting on a wheel (left or right), hence torque, T

$$T = \frac{Fcos\theta}{2} \times r_{wh} \quad (21)$$

F = Horizontal force acting on a wheel (left or right) $= Fcos\theta$

Here, Friction force, $F_f = \mu_k \times N$ [Neglected] (22)

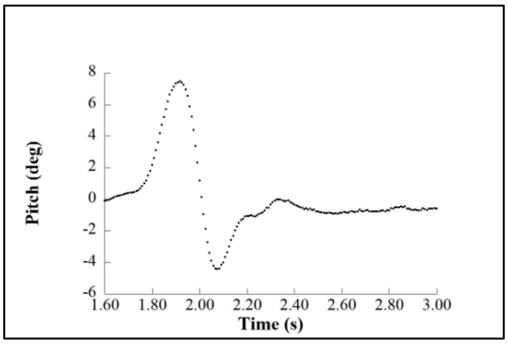
Where, μ_k= kinetic co-efficient of friction, N = Normal component of reaction of the surface. Now,

$$M = \text{Total mass} = \text{mass of robot body} + \text{mass of wheel} = m_b + m_{wh} \quad (23)$$

The proposed model is designed as like the pendulum on cart which consists of a thin vertical rod attached at the bottom, referred to as pivot point mounted on a mobile toy car. The car, depending upon the direction of the deflection of the pendulum moves horizontally in order to bring the pendulum to absolute rest.

7. Results

Initially the parameters are set to the components of Segway like robot and as the force is unknown, the speed and pitch data are cropped at the time of the maximum pitch. At that time, no external force is applied. Therefore, system is completely described by the numerical values of the states. Speed response and experimental pitch are given as desired outputs. Until a satisfactory response is found, identification routine is run several times. When the location of center of mass and inertias of the wheels are allowed to change, the best result is obtained.



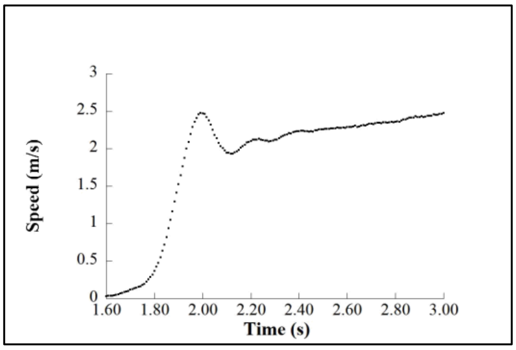


Fig. 7.1 Experimental Pitch Response

Fig. 7.2 Experimental Speed

Applying feedback the PID tuning has been started with $K_p = 0$, $K_i = 0$ and $K_d = 0$. Then finally we get the values which are shown in Table 1.

Table 1. Data table for the parameters, K_p, K_i, K_d

Controller	K_p	K_i	K_d
PID	100	2	0

There is a standard set of values of parameters K_p, T_i and T_d and according to a formula [9], 'Table 2' is shown in the following:

Table 2. Data table for the parameters K_p, T_i, T_d

Type of Controller	K_p	T_i	T_d
P	0.5 K_{cr}	∞	0
PI	0.45 K_{cr}	(1/1.2)P_{cr}	0
PID	0.6 K_{cr}	0.5 P_{cr}	0.125P_{cr}

11. Conclusions

The main goal of this work is to develop a two wheel self-balancing vehicle which will be simple in design and ease in controlling. The idea of developing this type of system is to design vehicles which carries people in short distance and avoid traffic jam. This work is successfully completed by satisfying all the requirements. Development of self-balancing two wheel electric vehicle using Arduino is a new approach for the personal transporter. Besides from transport human as loads, the vehicle also designed with compact and lighter weight that consumes less space and energy to carry. Since the complementary filter has been worked well, the more complex Kalman filter has not been implemented. The self-balancing of the robot can be improved if other tools like fuzzy controller or neural networks can be utilized. The frictional resistance of the wheels can be decreased if good quality bearings can be used in the system.

12. References

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