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Design and Implementation of an Experimental Segway Model ⋆

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Abstract: The segway is the first transportation product to stand, balance, and move in the same way we do. It is a truly 21st-century idea. The aim of this research is to study the theory behind building segway vehicles based on the stabilization of an inverted pendulum. An experimental model has been designed and implemented through this study. The model has been tested for its balance by running a Proportional Derivative (PD) algorithm on a microprocessor chip. The model has been identified in order to serve as an educational experimental platform for segways.

Keywords: Inverted pendulum, segway, nonlinear control.

1. INTRODUCTION

THe building of a device to transport a person from point A to point B has been done many ways in the past. This includes bikes, cars, planes, scooters and so on, recently there has been a new way of traveling, which is the segway [1]. The Segway uses the idea of an inverted pendulum which is a classic non linear control problem. There are several variations of the problem, the main ones are: the Furuta pendulum (Furuta, 2003) [4], (Astrom and Furuta, 1996) [2], the pendulum on a mobile cart (Gordillo et al., 2004) [5], the pendulum on a two-wheeled vehicle with independent motors (Baloh and Parent, 2003) [3], (Grasser et al., 2002) [6], (Segway, 2004) [7], the Balancing Scooter (Blackwell 2007) [8], the Human Transport Vehicle (Beckwith, 2004) [9], the Almost Self-Balancing two Wheeled Electric Skateboard (Chudleigh, 2005) [10]. In addition, there is a wide range of controller systems, designed throughout the last few decades for these applications. This paper presents the design and implementation of an experimental segway model based on the stabilization of an inverted pendulum (Figure 1), this model has been identified in order to serve as an educational experimental platform for segways. This work focuses on the problem of an inverted pendulum on a two-wheeled vehicle for human transportation, where the person riding the vehicle acts as pendulum. The forward movement is caused by the rider's inclination with respect to the equilibrium position. The core of the system is made up of a microcontroller, whose function is to calculate the controller's actions using the information arriving from the various sensors. This microcontroller communicates with a PC, allowing collection of relevant vehicle data for analysis. The rest of this paper is organized as follows; Section 2 describes the different components of the system, and the relationship between them, both at hardware and software levels. Section 3 shows the mathematical model. Section 4 presents the controller design along with simulation results. Treatment of sensor information together with experimental results are addressed in Section 5. Finally in Section 6, conclusions and suggestions for future work are presented.

Fig. 1. General view of the vehicle

2. SYSTEM ARCHITECTURE

The system has a low-cost microcontroller (PIC16F877A, by Microchip) [12], which communicates with various peripherals. As it can be seen in Figure 2, there are two sets of devices connected to the microcontroller: sensors and actuators. The set of sensors is made up by a gyroscope and an accelerometer for balancing, and a potentiometer for steering measurements. The gyroscope and accelerometer were chosen from the Analog Devices iMEMS (ADXL203EB and ADXL203EB) [13, 14]. They report an analog voltage between 0V and 5V to the controller. The gyroscope is used simply to measure angular rate. The accelerometer is used to indirectly measure the direction of the force of gravity, since it is really sensing force per unit mass along a given axis. This, along with a small angle approximation, gives an estimate of the angle to horizontal. The system actuators are two geared electric motors that run on 24VDC and are able to reach 220 rpm.

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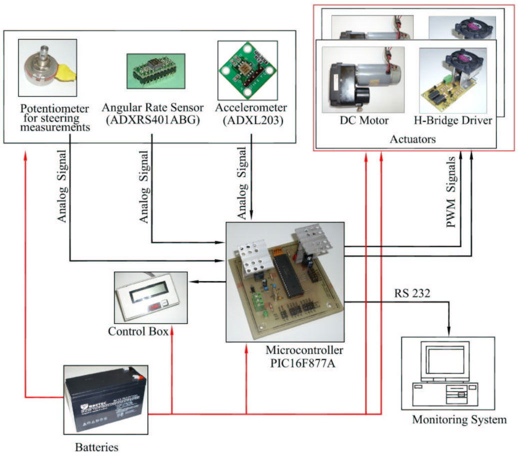

Fig. 2. Architecture of the system

Motor drivers were required to turn the control signal from the microcontroller into an appropriate varying power level to drive the motors. Figure 3 shows the view of the physical components from the perspective of underneath the board.

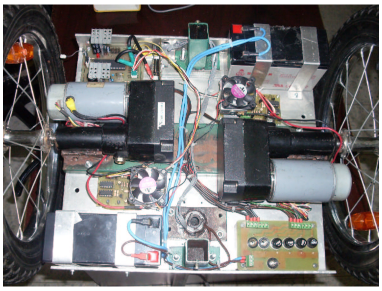

Fig. 3. The view of the physical components from the perspective of underneath theboard.

Pulse Width Modulation (PWM) is one method of communicating between a microcontroller and a motor driver. By sending a train of pulses at regular intervals and varying the width of the pulses, the motor driver is able to interpret this pulse width as a requested motor duty level. Two H-bridge FET motor drivers were designed to drive the motors. The communication with the microcontroller is through a standard RS-232. This link allows to have a connection between the microcontroller and the monitoring PC. All of the code on-board the segway was written in C and compiled using mikroC, mikroElektronika C compiler for Microchip PIC microcontrollers. The code's main loop runs at about one hundred times per second (100 Hz), which is more than adequate for keeping a person balanced. To carry out useful experiments, it is necessary to have a reliable way to monitor and store the data generated. This is the reason behind the development of a PC software application, with the aim of: monitoring the system variables in real time, storing the samples obtained in the experiment for subsequent study. This PC software application was implemented using Dot Net as shown in the Figure 4.

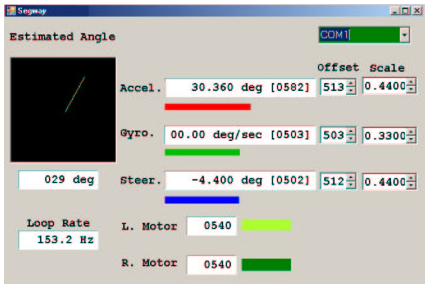

Fig. 4. View of the implemented visual basic application

3. SYSTEM MODELING

The system is basically made up of a platform that is mounted on two wheels activated independently by two DC motors. On this platform, there is a mass that can be represented as a mass point at a distance *l* from the base plane. By looking at previous attempts of self-balancing vehicles and mobile inverted pendulums, a suitable free body diagram was found. The model chosen was based on the Grasser model [6], but with some simplification of the equations. The equation of motion for a two-wheeled inverted pendulum and linear model for a DC motor was derived. The pendulum and wheel dynamics are analyzed separately at the beginning, but this will eventually lead to two equations of motion which completely describes the behavior of the balancing problem. Three bodies were used, the two rotating masses of the wheels and the chassis/person combined body, which was represented using a single point mass a certain distance from the axle. The latter was possible as it was anticipated that the person would be significantly heavier than the base itself. Figures 5 and 6 show the free body diagram for both wheels and the chassis.

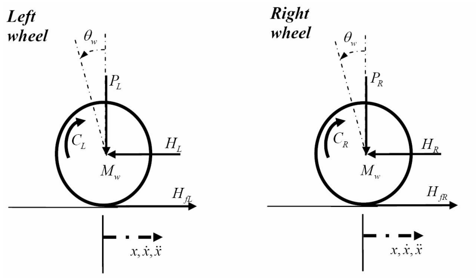

Fig. 5. Free body diagram of the wheels

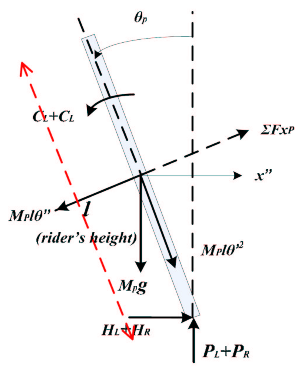

Fig. 6. Free body diagram of the chassis

Table 1. Definitions of parameters of the system.

Parameter	Definition	Value
x	Distance	m
$\dot{x}$	Speed	m/s
$\ddot{x}$	Acceleration	m/s^2
φ	Error angle	rad
$\dot{\varphi}$	Error angular speed	rad/s
$\ddot{\varphi}$	Error angular acceleration	rad/s^2
k_m	Constant of the motor torque	0.869 N/A
k_e	Constant of the motor's back-EMF	0.083V/rad
l	Length of the pendulum	1.7m
r	Wheel radius	0.2m
R	Resistance of the Motor	1Ω
M_p	Mass of the pendulum	85kg
I_p	Moment of inertia of the pendulum	$68.98kg.m^2$
M_w	Mass of the wheel	3.5kg
I_w	Inertia of the wheel	$0.07kg.m^2$
g	Acceleration of gravity	$9.8mls^2$

The linearized state space equation for the system is obtained as shown in Equation (1).

$$\begin{bmatrix}\dot{x}\\ \ddot{x}\\ \dot{\varphi}\\ \ddot{\varphi}\end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0\\ 0 & \dfrac{2K_mK_e(M_plr - Ip - M_pl^2)}{Rr^2\alpha} & \dfrac{M_p^2gl^2}{\alpha} & 0\\ 0 & 0 & 0 & 1\\ 0 & \dfrac{2K_mK_e(r\beta - M_pl)}{Rr^2\alpha} & \dfrac{M_pgl\beta}{\alpha} & 0\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ \varphi\\ \dot{\varphi}\end{bmatrix} + \begin{bmatrix}0\\ \dfrac{2K_m(I_p + M_pl^2 - M_plr)}{Rr^2\alpha}\\ 0\\ \dfrac{2K_m(M_pl - r\beta)}{Rr\alpha}\end{bmatrix}V_a. \quad (1)$$

Where $\alpha = I_p\beta + 2M_pl^2(M_w\frac{I_w}{r^2})$, $\beta = 2M_w + \frac{2I_w}{r^2} + M_p$.

This model of the system assumes that the wheels of the vehicle will always stay in contact with ground and there is no slip at the wheels. Cornering forces are also considered negligible. In this model, the definitions of parameters and there values are shown in Table 1.

Based on the parameter values shown in table 1 the state space equation and the transfer function for the system is obtained as,

$$\begin{bmatrix}\dot{x}\\ \ddot{x}\\ \dot{\varphi}\\ \ddot{\varphi}\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0\\ 0 & -0.1124 & 22.3451 & 0\\ 0 & 0 & 0 & 1\\ 0 & -0.0493 & 14.7678 & 0\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ \varphi\\ \dot{\varphi}\end{bmatrix} + \begin{bmatrix}0\\ 0.2709\\ 0\\ 0.1189\end{bmatrix}V_a \quad (2)$$

$$G(s) = G_1(s) + G_2(s)$$

$$G_1(s) = \frac{X(s)}{V_a(s)} = \frac{0.2709s^2 - 1.3438}{s^4 + 0.1124s^3 - 14.7678s^2 - 0.5577s} \quad (3)$$

$$G_1(s) = \frac{\varphi(s)}{V_a(s)} = \frac{0.1189s^2}{s^4 + 0.1124s^3 - 14.7678s^2 - 0.5577s} \quad (4)$$

The schematic block diagram for this open loop system is shown in Figure 5.

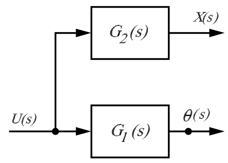

Fig. 7. Schematic block diagram for the open loop system

4. CONTROL SYSTEM DESIGN

In this section, our aim is to show how the system can be controlled using classical PD controllers. The controller is designed utilizing the dynamic model developed for the balancing a two wheeled inverted pendulum in the previous section. Because the system is inherently unstable, an impulse input applied to the open loop system will cause the tilt angle and position of the vehicle to rise unboundedly. Figure 8 shows the simulation when an impulse input is applied to the uncontrolled system.

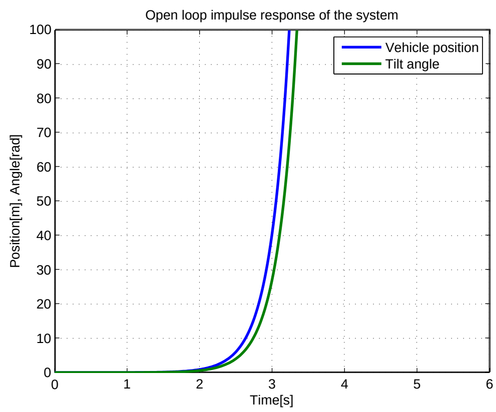

Fig. 8. Open loop impulse response of the system

We will implement a PID controller which can only be applied to a single-input single-output (SISO) system, so we will be only interested in the control of the pendulums angle. Therefore, none of the design criteria deal with the vehicle's position. The control of this problem is a little different than the standard control problems we may be used to. Since we are trying to control the pendulum's position, which should return to the vertical after the initial disturbance, the reference signal we are tracking should be zero. The force applied to the vehicle can be added as a disturbance. The schematic for this problem is shown in Figure 8.

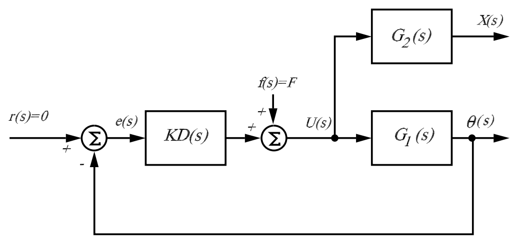

Fig. 9. Schematic block diagram for the closed loop system

To simulate this control problem we used MATLAB Simulink, we will start with our open-loop model of the inverted pendulum, and add in both a control input and the disturbance input to the plant. The Simulink model of linearised model of control system is shown in Figure 11.

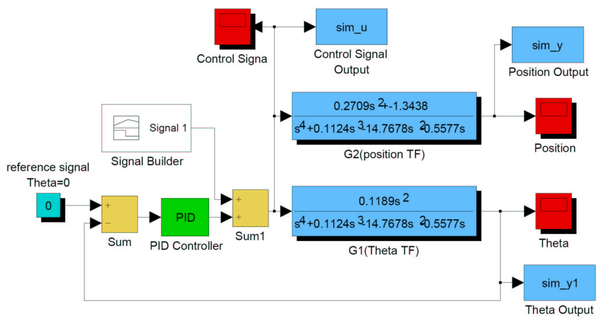

Fig. 10. Simulink model of linearized model of control system

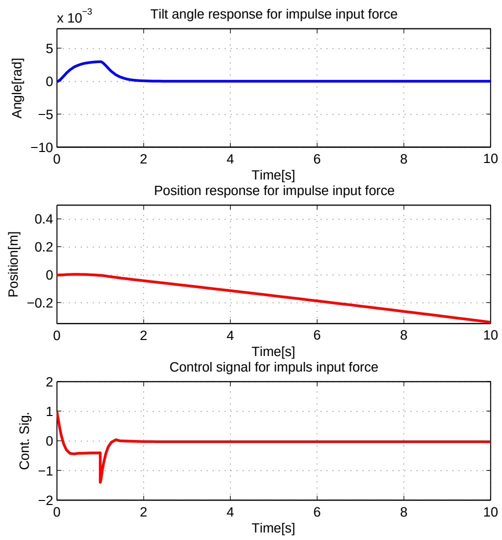

Fig. 11. Response for impulse input force with PID control parameters: k=450, kd=100, ki=0

5. THE BALANCE FILTER AND EXPERIMENTAL RESULTS

There are a number of problems with using direct sensor data for control. For one, with electric motors on the same power and ground line as the controller, there is bound to be noise in the system even with a power supply filter capacitor for the controller. There are also physical reasons why the data from the accelerometers and gyroscope has to be filtered. The accelerometers measure a change in angle by the component of the force of gravity along their sensitive axis (horizontal). But they also report other horizontal accelerations from the motors. The gyroscope measures angular rate and can be used to estimate angle by integration. But this method can lead to drift. The tow axis accelerometer measures acceleration, but really force per unit mass and can be used to measure the force of gravity. Above, X-axis reads 0g, Y-axis reads -1g (Figure 13). For a balancing platform, the most important angles to measure are near vertical. If the platform tilts more than 30 degrees in either direction, theres probably not much the controller can do other than drive full speed to try to catch it. Within this window, we can use small angle approximation and the X-axis to save processor time and coding complexity. If the platform is tilted forward by and angle θ, but stationary (not accelerating horizontally), X-axis reads: $(1g) \times sin(\theta)$, for the small angle approximation $sin(\theta) = (\theta)$ in radians.

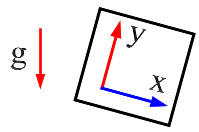

Fig. 12. Measuring the force of gravity above x and y axis

The first step is to read in analog inputs (through the analog-to-digital converter, ADC) for each sensor and get them into useful units. This requires adjustment for offset and scale as follows,

$$Acc. = (Acc.ADC - Acc.ADCoffset) \times Acc.ADCscale$$

$$Gyro = (GyroADC - GyroADCoffset) \times GyroADCscale$$

In order to control the platform, we must know both the angle and the angular velocity of the base platform. This should be the basis for an angle PD (proportional/derivative) control algorithm, which has been proven to work well for this type of system [9].

$$MotorOutput = K_p(Angle) + K_d(AngularVelocity) \quad (5)$$

The filter described in [7] has been used for this application.This filter consists of two parts of filters always add to one, so that the output is an accurate, linear estimate in units that make sense. A block diagram of the used balance filter is shown in Figure 15.

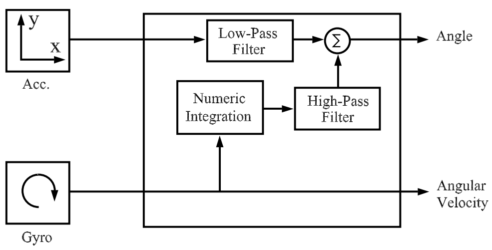

Fig. 13. The block diagram of the used balance filter

It has been shown in [7] that the angle in this filter may be approximated as:

$$angle = (0.98) * (angle + gyro * dt) + (0.02) * (acc). \quad (6)$$

The first part of this quation resembling a high-pass filter on the integrated gyro angle estimate. It will have approximately the same time constant as the low-pass filter. The second is a low-pass portion acting on the accelerometer. If this filter were running in a loop that executes 100 times per second, the time constant for both the low-pass and the high-pass filter would be:

$$\tau = \frac{a.dt}{1-a} = \frac{0.98 \times 0.01}{0.02} = 0.49 \quad (7)$$

This defines where the boundary between trusting the gyroscope and trusting the accelerometer is. For time periods shorter than half a second, the gyroscope integration takes precedence and the noisy horizontal accelerations are filtered out. For time periods longer than half a second, the accelerometer average is given more weighting than the gyroscope, which may have drifted by this point. Some experimental rsults are shown in Figure 16

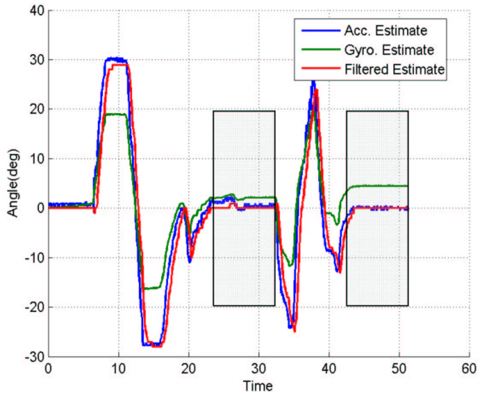

Fig. 14. Experimental results for Sample Rate of 98 Hz and filter Coefficients of 0.98 and 0.02

Notice how the filter handles both problems, horizontal acceleration disturbances while not rotating. Having completed the controller design, a set of experimental results was made. This allows to check its operation and to fine-tune the parameters of the controller. The signal that comes from the controller, corresponding to the force to apply to the cart, is spread in a symmetric way between the two wheels of the vehicle. Moreover, steering is obtained using a proportional control that increases the force exerted on one of the wheels while decreasing it on the other, producing the desired turning. Figures 17 and 18 show the response of the system for different initial tilt angles.

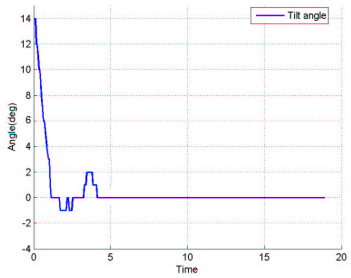

Fig. 15. Response for initial tilt angle of 14 deg

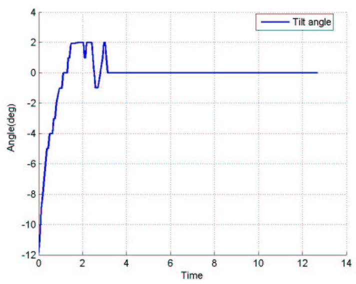

Fig. 16. Response for initial tilt angle of -12 deg

6. CONCLUSION

This paper presents a segway whose behavior is based on the stabilization of an inverted pendulum. This vehicle has been manufactured using low-cost commercial components. An experimentation system has been obtained and allows to test various controllers.The model has been tested for its balance by running a Proportional Derivative (PD) algorithm on a microprocessor chip. The model has been identified in order to serve as an educational experimental platform for segways. Future developments will include designing new control techniques and performing a comparative study among them.

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