TWO W]

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ABSTRACT

This project discusses about the development of a 2 wheel balanced autonomous robot based on the inverted pendulum model. The vehicle is designed to achieve stability as it stand still and able to move around a smooth terrain without falling. An IMU which consist of triple-axis accelerometer and dual-axis gyroscope was chosen as the sensor to calculate the tilt angle of the robot. This sensor needed to be placed near the centre of the robot to make the reading more accurate. A processing unit chosen is the Arduino Mega, a PIC based microcontroller which can be used to read both the data send from the sensor and the motor encoder. It can also send the output signal towards the motor and can easily be program by the use of its own programming language. A PID controller is used in order to calculate the "error" value as it finds the difference between the desired output and the measured outcome. This value is then sent as a feedback data towards the input to adjust and minimize the error.

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LIST OF ABBREVIATIONS

PID	Proportional-Integral-Derivative
DOF	Degree of Freedom
IMU	Inertial Measurement Unit
DC	Direct Current
ZMP	Zero Moment Point
COG	Center of Gravity
EOPD	Electro-Optical Proximity Detector
IRPD	Infrared Proximity Detector

CHAPTER 1

INTRODUCTION

1.1 Introduction

A two wheel balanced vehicle are a vehicle that can stand on its own two wheels without falling either to the front or back in a sense that it can balance itself. Though this vehicle already existed and sold throughout the world by a commercial company named Segway, to tackle the problem that it pose and to create such vehicle with a real world application would be not only challenging but also interesting.

More importantly, the control system for the two wheeled balanced vehicle have many applications in the area of automobile, robots and such that it inspired research institute, commercial companies and independent hobbyist to develop and implement their own system. A two wheeled balanced vehicle would offer greater advantages over other platforms such as three wheeled or four wheeled as it can:

- Turn a sharp corner or spin entirely 360 degrees on its spot.
- Navigate easily on various terrains.
- Provide higher speed due to less friction from lesser wheels used.
- Have a simple design.
- Lessen the parts needed to repair the vehicle.

The vehicle, in order to balance itself need to be able to do the following task which is to detect its current state, either in equilibrium or not, sends the data to the controller, and actuate the motor that will provide the necessary force should the vehicle are in a state of unbalance. The first task can be accomplished with the help of electronic sensor. A suitable sensor needed to be placed in the robot so that it can measure its current state and send the signal towards the controller. There are a lot of sensors which can be used to do so. Next would be to implement the controller. The controller must be able to read the data from the sensors, perform a calculation and determine whether it needs to activate the actuator. The controller should be cheap and effective, not to mention fast so that the robot can constantly balance itself without falling. The actuator would be in the form of a motor with a high speed and torque. This is due to the fact that the motor will do the work to balance the force of the vehicle. Should the motor run too slow, the vehicle might reach a pitch angle in which the motor might no longer have the necessary torque to balance it. And should the torque of the motor is too weak, it can never balance the vehicle as the weight is too much to overcome it.

1.2 Problem Statement

A two wheeled robot that is either standing still or moving can be hard to stabilize especially if it has a high center of gravity. This is because higher center would give out a greater moment towards its feet and would require a greater force to compensate with the said moment. It is preferable to have a robot with a lower center of gravity as it would help reduce the torque needed to balance itself.

Moreover, noise read from the sensor might also pose a problem. The noise will cause the sensor to give out inaccurate reading in which could be amplified when calculated by the controller. Therefore it is preferable that the sensor used would give out as minimum noise or errors as possible. If not, a filter must be implemented to keep the noise from harming the robot's system.

Another problem that might occur is the controller. The controller used needs to be efficient and fast so that the robot can balance itself in time. If the controller were to take a long time to do the calculation, its output which is to actuate the motor would have been for nothing as the vehicle itself might have already collapse to the floor. Thus the controller developed should be simple yet robust as to be able to read the variables and actuate the motor to give out the necessary force to balance the vehicle.

1.3 Objective

- To design a robot that is capable of stabilizing itself, move to a desired spot without falling.
- To implement a control system in an autonomous robot.
- Filter the noise from the sensor to give an accurate reading.

1.4 Scope

The created robot should be able to balance itself while it is being left in a stand still. It should also able to move around a smooth terrain without fail. Furthermore, the movement of the robot should be as smooth as possible, avoiding jittery movement as to prevent a constantly recalculation of error value.

1.5 Organization of Report

This thesis consists of 5 chapters. The first chapter is the Introduction where a background study of the project is done. Chapter 2 would highlights on all the literature review upon articles, journal and etc. Chapter 3 is where the methodology for the project is further explained. The next chapter is the results and experimentation done in order to make the project a success. It is also where a discussion regarding to the obtained results would be done. Finally, Chapter 5 will conclude the project and provide a few recommendations for the project.

1.6 Plan of Work

No	Subject/Month	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
1	Title Confirmation										
2	Set Objective and Scope										
3	Problem Statement										
4	Literature Review										
5	Research Methodology										
6	PSM 1 Report										
7	PSM 1 Presentation										
8	Tools Preparation										
9	Experiment Process										
10	Data Collection										
11	Data Analysis										
12	PSM 2 Report										
13	PSM 2 Presentation										

Table 1.1: Plan of work for final year project.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction.

By having a literature review, a research project can bé easily updated and kept tracked as it provides the researcher with the information needed to create and finish the project. It also helps the researcher by giving them an idea on how to tackle the problems posed by reviewing the methodology used by other institute or individuals. This chapter provides the key topics that are related to the two wheeled balanced vehicle.

2.1 Balancing Bots.

An inverted pendulum model is quite common among control engineering for it is often used as a benchmark in testing control strategies. The model is unique and has wide application therefore had drawn interest from many researchers and robot enthusiast all around the world. A balancing bot is one of the systems that are based on this model as it can balance itself and/or its driver. The derivations of the model also have been implemented in the following area such as designing a legged robot, a robotic wheelchair, and personal transport system.

Researchers at Industrial Electronics Laboratory at the Swiss Institute of Technology have built a two wheel robot prototype based on Digital Signal Processor, namely JOE. JOE is a mobile inverted pendulum, a vehicle which could balance its driver on two coaxial wheels. A robot based on a linear state controller, it is composed of a chassis carrying DC motor, a DSP board, a power amplifier, a radio control receiver and a vertical steel bar with weight attached to it in order to simulate the weight of a driver. It uses the information given from a gyroscope sensor and motor encoders to know its current system state. The robot is limited to 3 Degree of Freedom (DOF) as it has the ability to rotate around the z-axis (pitch), make a linear movement of the chassis around the x-axis (surging), and the rotation around its vertical axis (yaw). (Grasser et al, 2002).

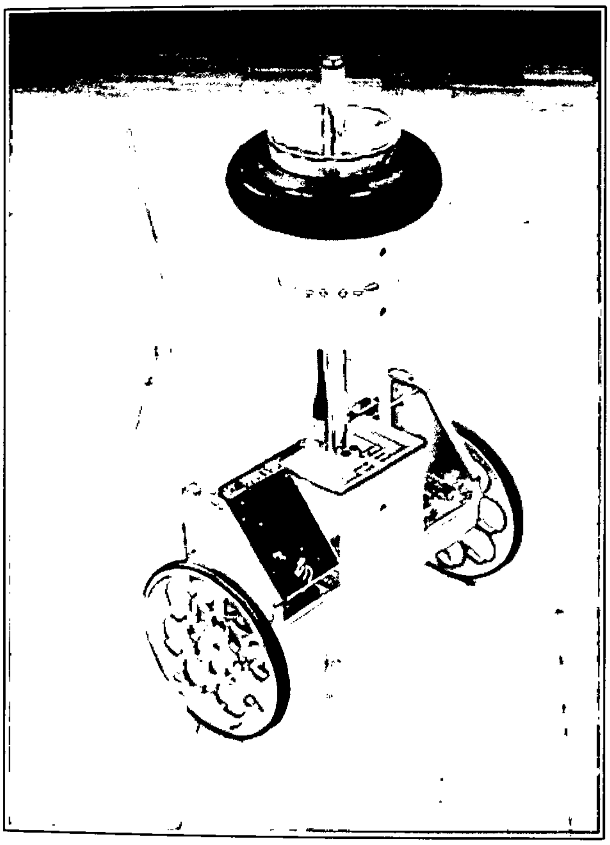

Fig. 2.1: JOE, mobile inverted pendulum (Grasser et al, 2002)

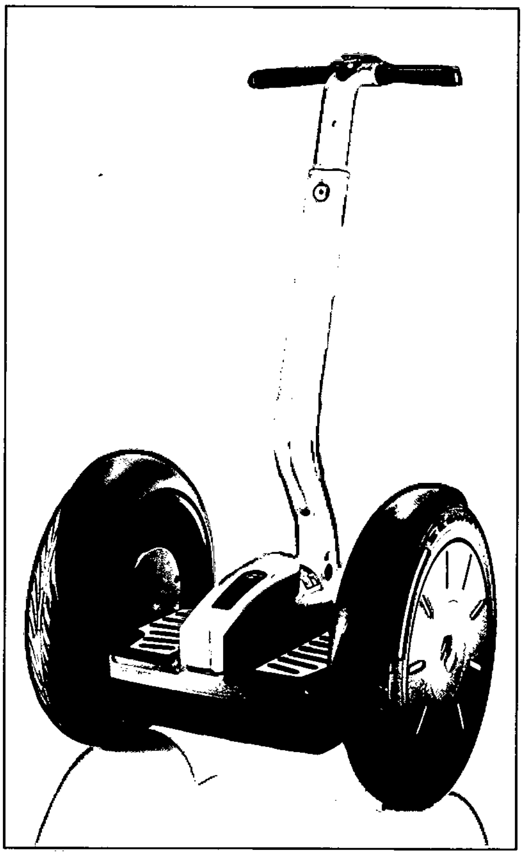

Fig. 2.2: Segway PT (http://www.segwaytexaswest.com)

There's also a two wheeled robot which can be seen on movies, films and TV shows, created by Dean Kamen. Dubbed the name 'SEGWAY HT' (HT for Human Transporter, though a new suffix has been implemented, PT which stands for Personal Transporter), it is commercially available at a price. Dean Kamen, a man who holds more than 150 U.S. and foreign patents related to medical devices, climate control systems, and helicopter design, had invented the Segway to balance a human standing on its platform while the users traverses the terrain. The system compromised of 5 gyroscopes, tilt sensors to keep itself upright and a few extra features in order to balance its user and navigate the terrain. Though it only needed 3 gyroscopes for the whole system, additional sensors are attached to it for extended safety precaution. (Dean Kamen, 2001)

On another subject, Louis Brennan, an Irish-Australian inventor, was the first to patent a gyroscopic stabilizing vehicle. His work in ensuring a monorail kept upright by a gyrostat (a modified gyroscope) leads him to create and patent a gyroscopically-balanced monorail system in 1903, which he intended it for military use. By mounting one or more gyrostats along the body, the monorail can balance itself if its equilibrium is disturbed; as he successfully demonstrated the system in a full scale on 1909, at Gillingham, England. Though the system was a success, he prevented the mass produce of the monorail in fear that the gyrostats would fail, causing a total system failure. (Louis Brennan, 2012) (Monorails in History, Part 1, 2012). A group from Columbia University had manufactured a modernized version of Brennan's monorail. Unfortunately, the group was unable to create a working model. The electric component of the model would continuously overheat during operation, causing the motor to burn out. The electronic segment was improperly modeled, which led to the mechanism's failure. (Carter et al, 2005, Columbia University). There is also another group from University of Michigan that had tried to improve the design and create a functioning model. However, they too had failed as their prototype didn't work due to the lack of time for testing (they are to present their system to the Michigan's University Design Expo). (Akinlua et al, 2007, University of Michigan).

Another similar robot to JOE was the nBot, created by David P. Anderson (2012). This small scale robot was first created as an experiment to learn to control inverted pendulum. The nBot first revision (Rev 1) shows that the robot uses a low-friction 5k potentiometer (installed at the ball-bearing pivot) to measure the tilt angle. At this stage, the robot has 3 wheels and the ball-bearing pivot used was attached with a 3 foot (0.91m) wooden pole topped with an orange Nerf Ball. In Rev. 2 however, the ball-bearing pivot was placed at the bottom of the robot and the wooden pole was replaced with a short aluminium feeler that touches the floor. This method allows the robot to sense its angle to the floor and the nBot was rebuilt as a two wheeled robot. The design of the nBot was further changed in Rev. 3 and the ball-bearing pivot and angle sensor were changed with a commercially available inertial sensor. It is also can be noted that the nBot has won the NASA cool robot of the week in the year 2003. The latest revision for the nBot up to this date is the Rev. 4 where the robot uses a new base and motor.

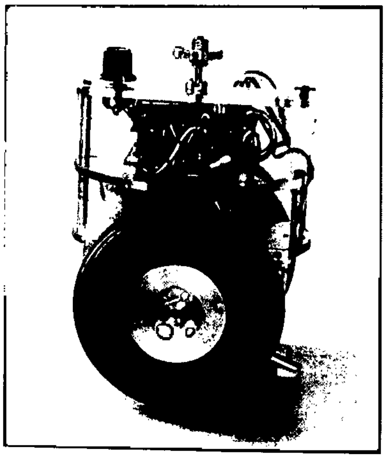
Fig. 2.3: nBot Rev.2

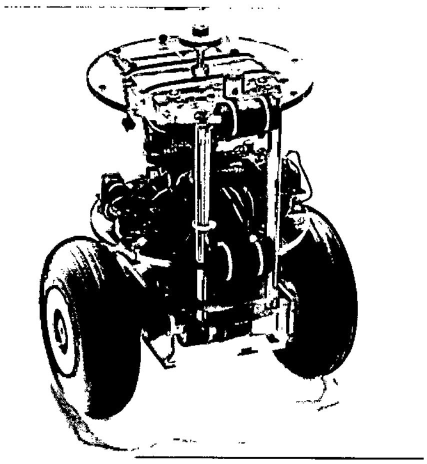
Fig. 2.4: nBot Rev.3

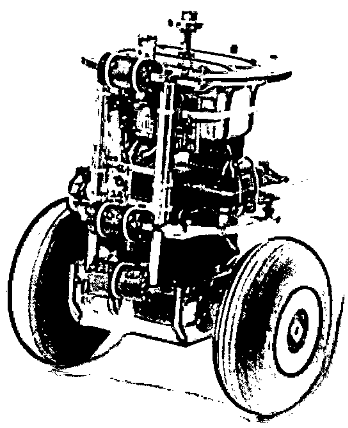
Fig. 2.5: nBot Rev.4

(http://www.geology.smu.edu/~dpa-www/robo/nbot/)

Steven Hassenplug (2012) had also created a balancing robot. However, his design is a bit more peculiar due to the fact that he did not use a gyroscope sensor, for he uses two Electro-Optical Proximity Detectors (EOPD) in order to provide the tilt angle information.

The EOPD is based on the IRPD (Infrared Proximity Detector) circuit, but used visible light to determine the distance. The robot was constructed by the use of LEGO Mindstorms robotics kit and BrickOS, a C/C++ like programming language specifically for the LEGO Mindstorms. The robot which was called Legway, was voted into the Hall of Fame at LEGO Mindstorms Monthly and was selected as the Cool Robot of the Week by NASA.

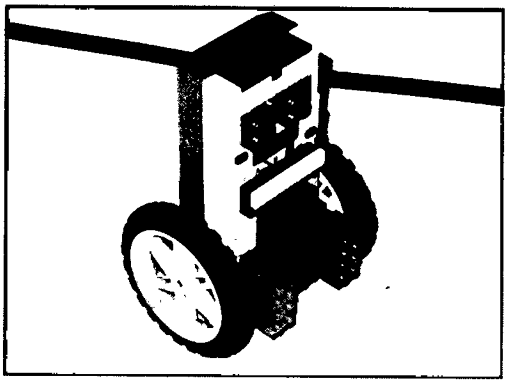

Fig. 2.6: Legway (http://www.teamhassenplug.org/robots/legway/)

There are also other studies that had implemented the problems posed by an inverted pendulum model. A paper titled 'Cooperative Behavior of a Wheeled Inverted Pendulum for Object Transportation' was published in order to show the interaction of forces between objects and robot (Shiroma et al, 1996). The paper mentioned that there are other studies of cooperative behavior that has been done, but most of the studies had assumed that the forces of the object do not influence the stability of the robot. In their study, they had consideration that the interaction of the object and each of the robots would influence its stability. By doing so, they can highlights the possibility of cooperative transportation between two similar robot and between human and robot.

In Japan, a concern in the rapid increase of aged population had prompted the development of a robotic wheelchair. This is because a wheelchair bound person needed an assist when traversing on a road with many steps/curbs. The researchers from Kanagawa Institute of Technology had proposed a wheelchair with the control system of an inverted pendulum when encountered with such road. The wheelchair should be able to climb over the steps up to about 10cm (Takahashi et al, 2000).

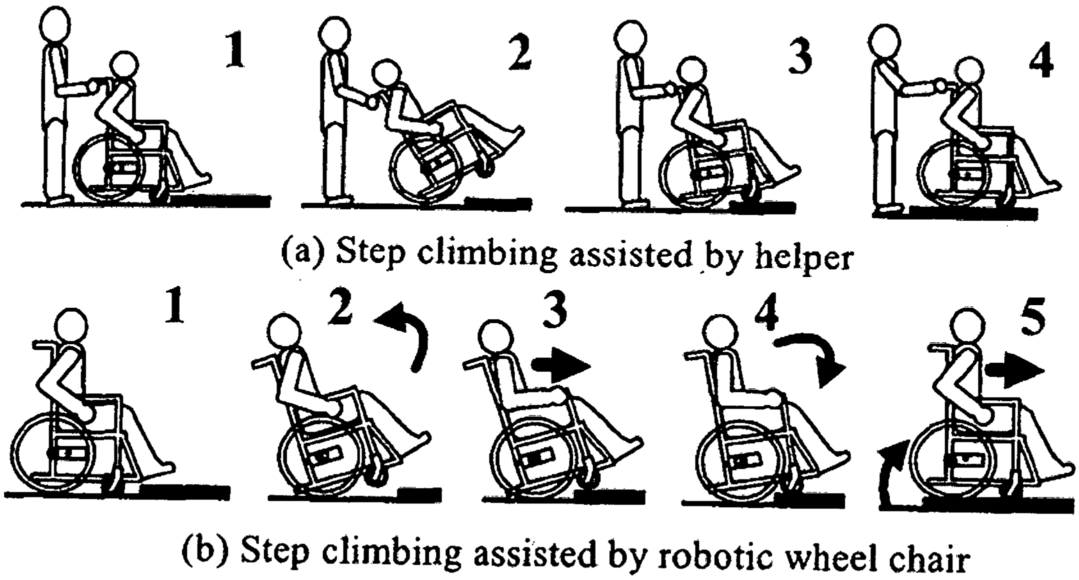

Fig. 2.7: Concept of step climbing using robotic wheelchair (Takahashi et al, 2000)

On a higher level, Sugihara et al. (2002) had modeled a walking motion of a human as an inverted pendulum. Their goal is to provide humanoids with high-mobility, developing a real-time motion generation method unlike the trajectory replaying method. The method that they've developed had proven able to provide humanoids with superior adaptability and agility, namely, high-mobility essential for robots to act and support human beings in the real world. This method used the dynamical relationship between Zero Moment Point (ZMP) and the center of gravity (COG).

2.2 Sensor

A two-wheeled vehicle is naturally unbalanced thus require an external force to balance itself. In order to do so, the system must be able to do the following; sense a disturbance in the vehicle equilibrium, feed the information to the controller, and actuate a device that will provide the necessary force to balance the system. There are abundant types of controller that can read the information as is discussed below and the development of both the controller and actuator will be further told in Chapter 3. As for the device to read the disturbance of the system, or the sensors, it must also be evaluated in order to know the capabilities and weakness of each sensor.

In order to balance the robot, there are a few variables that need to be known such as the pitch angle, the pitch rate, the chassis speed, etc. Such variables can be measured by the use of sensors. The most common sensor used by balancing bots researcher and/or enthusiast is the combination of two of these three sensors: Gyroscope, Accelerometer, and Motor Encoder. This is because the gyroscope can directly measure the pitch rate, whilst the pitch angle can be found by integrating the data given. The speed of the vehicle can be read by using either accelerometer or the motor's encoder. The combination of sensors between a gyroscope and encoder are those which have been implemented by Grasser et al (2002), Jeong et al (2007) and Takahashi et al (2001).

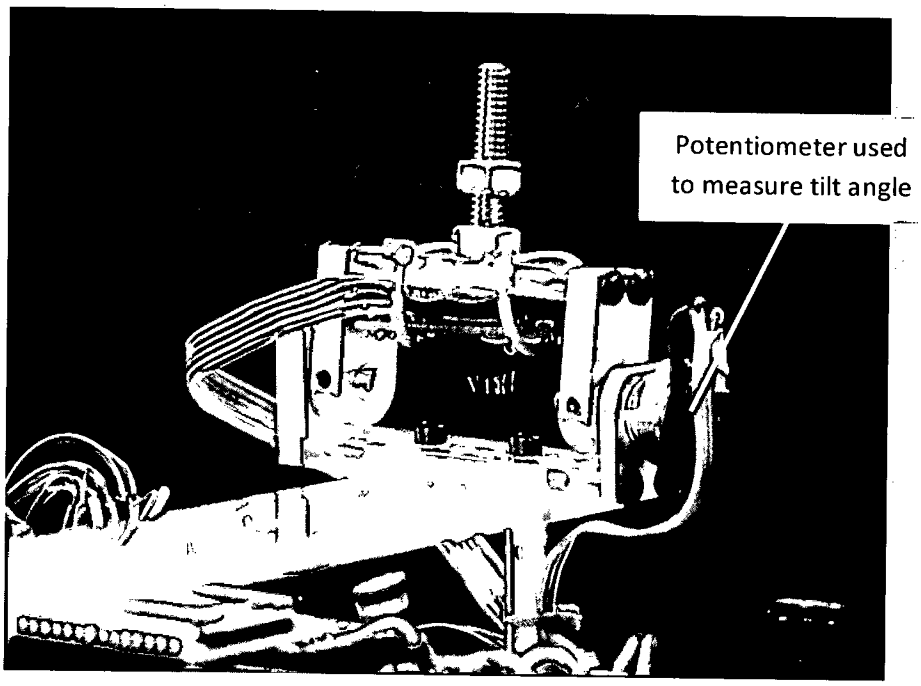

Fig. 2.8: Potentiometer used on nBot Rev.1

(http://www.geology.smu.edu/~dpa-www/robo/nbot/b04.jpg)

The same can be said with nBot. nBot is currently using a commercially available inertial sensor and position information from motor encoder. But the first revision of the nBot was using the data given from a low-friction 5k potentiometer. A ball-bearing pivot connected with either a 3 foot wooden pole (Rev.1) or a short aluminium feeler touching the floor (Rev.2) can give the data needed to measure the tilt angle. It poses a question that perhaps a potentiometer is enough to give out the necessary reading to the controller in order to balance the robot. This shall further be investigated in Chapter 3.

Speaking of using a potentiometer, it worth noting that there is a study done that tries to implement the two wheeled balance method upon a four wheeled vehicle (Arndt et al., 2011). In the paper, it is stated that in the United States in 2005, 21.1% of a total of 54,718 deaths in vehicle crashes were caused by rollover. As a four wheeled vehicle, there are 3 DOF of the rigid body (excluding the translational DOFs). In order to control those 3 DOF (the yaw, pitch and roll), he had proposed the use of 3 sensors which is the potentiometer, accelerometer and the gyroscope. The potentiometer is used to measure the roll angle of the vehicle. It is measured using a hinged linkage that rolls along the ground next to the vehicle while connected to the chassis through the potentiometer. Sensors such as gyroscope and accelerometer would read the angular rate and the speed of the vehicle. Such applications of the potentiometer would not apply to a two wheeled robot as it does not have the roll orientation. However, if there were a need to calculate the roll angle (maybe an application in which the robot might traverse along an uneven road that causes it to wobble along the roll orientation), the idea given could be used.

Steven, the creator of Legway, had attempted to build his robot using an accelerometer as his sensor, but soon realized that the acceleration due to gravity would not change when the robot tilts. According to him, the sensor will always give out a zero reading until it smashes to the floor. Therefore, he had to use another type of sensor which is the Electro-Optical Proximity Detector (EOPD) to balance the robot. The EOPD is based on IRPD (Infrared Proximity Detector) circuit, with the difference in which the EOPD uses the visible light to measure distance rather than using the infrared wavelengths. The sensor can measure the distance by checking the detector, sending a pulse of light, and checking the detector again to calculate the amount of light reflected. The value read will change according to the distance of an object and the color of the object. A small value change would indicate a change in distance while a large value change indicates a change in surface color (such as from white to black). EOPD however does have a weakness as it usually does not return a usable distance to black surface, due to the light is being absorbed. IRPD can be used to replace EOPD but it work well in detecting/following lines as the sensor detects a different wavelength of light (note that the EOPD used on Legway give out the data needed for it to balance itself and detect/follow lines).

A project done by a group from University of Michigan had chosen to use only gyroscope for the data acquisition (Akinlua et al, 2007). They however, had proposed 4 concepts in which a gyro can be used to balanced their system (which is a gyroscopically balanced monorail based on Louis Brennan). The 4 aforementioned concepts are:

- Single Gyro Single Wheel
- Single Gyro Two Wheels
- Twin Gyros Two Wheels
- Single Fluid Gyro Two Wheels

After discussion and comparison, they had chosen to go with the concepts of their predecessors which are the Single Gyro Two Wheels. This is because upon their research, they have concluded that the Single Gyro Single Wheel, or The Big Wheel, is complex in design, lack in information and an expert on the project would cause them to exceed their project schedule. The Twin Gyros Two Wheels concept is also discarded due to its disadvantages outweigh its advantage whilst the Single Fluid Gyro Two Wheels is unsafe and would result in unacceptable current draw, large batteries and large actuating motor.

An IMU (inertial measurement unit) is an electronic device which consists of accelerometer and gyroscope (sometimes an additional sensor which is magnetometer). It can measure and reports a system velocity, orientation and gravitational force. This device is being embedded into common user interface devices more frequently. Examples would include VFX1 virtual reality headtracking system, the Gyro Mouse (a wireless 3D pointer), and Microsoft's SideWinder tilt-sensing joystick (Ari Yosef Benbasat, 2000). His work concluded that human movement (gestures) can be tracked and recorded by the use of inertial measurements as the three single-axis gyroscope would measure the rotation whilst the acceleration of the human body is measured with two two-axis accelerometers.

2.3 Kalman Filter.

In 1960, a paper was published with the title 'A New Approach to Linear Filtering and Prediction Problems' by R.E. Kalman (Kalman, 1960). The research was done with the intention to overcome the limitations of the 'Weiner-Hopf' filter is solving problems of statistical nature. The process described within came to be known as Kalman filtering.

The filter which is also known as linear quadratic estimation (LQE) uses a set of mathematical equations that provides an efficient computational solution of the least squared method (Ooi, 2003). It is very powerful as it can estimates the past, present and even future states, and it can do so even when the precise nature of the modeled system is unknown. Kalman filter used the measured data from sensors over time, which of course contains noise and other inaccuracies, and produce a statistically optimal estimation of the underlying system state.

The Kalman filter has numerous applications in technology, mainly when dealing with applications that need guidance, navigation and control of vehicles, such as aircraft or spacecraft (in this case, the balancing robot's movement). Furthermore, the Kalman filter is a widely applied concept in time series analysis used is fields such as signal processing and econometrics.

Though the Kalman filter will not be applied in this paper, it's worth mentioning due to the fact that other papers, research and/or development of a balancing bot would implement it. This occurrence is due to the robot might require an accurate measurements of data. And as we know, the Kalman filter capable of such task. In fact, there are also lots of other papers that have been published which use the Kalman filter to filter the noise given from their sensor.

As Kalman filter is not applied, another method has been chosen to filter the noise. Suggested by Starlino (2012), the method that he developed was inspired by Kalman Filter, yet by far simpler and easier to implement. The main difference of his algorithm from Kalman filter is that the weight is relatively fixed, whereas in Kalman filter method, the weights are constantly updated based on the measured noise (this will be further discussed in Chapter 3).