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Two Wheeled Balancing Autonomous Robot

Mr. Stafford Michahial[1],Mr. Basavanna M[1], Dr.M.Shivakumar[2]

Asst. Professor, TE Department, GSSSIETW, Mysuru[1]

Professor & Head, EIE Department, GSSSIETW, Mysuru[2]

Abstract: A Two wheel balancing robot are based on inverted pendulum configurations which rely on dynamic balancing systems for balancing and maneuvering. The controller board is equipped with PWM channels and motion sensors such as accelerometers. The processes developed are involved in balancing a two-wheeled autonomous robot based on the inverted pendulum model. The robot utilises a Proportional-Integral-Derivative (PID) controlled differential steering method for trajectory control. The balancing robot platform proved to be an excellent test bed for sensor fusion using the Kalman filter as the methodology. Kalman filter is a set of mathematical equations that provides an efficient computational solution of least squared method. An indirect Kalman filter configuration combining free scale board accelerometers is implemented to obtain an accurate estimate of the derivative and tilt angle. An accelerometer measures acceleration of components that is mounted on it. In sensor world, accelerometer is very important because they can sense a wide range of motion. Accelerometer also detects the angle with respect to gravity. To run the left and right motors, two separate H-bridge are used. An H-bridge is an electronic circuit that enables the voltage applied across in either direction. The aim of the Accelerometer and PID readings is to control the direction of rotation of the DC motors.

Keywords: Accelerometer, Kalman filter, Inverted pendulum, PID Controller, H-bridge, Freedom freescale.

I. INTRODUCTION

The research on balancing robot has gained momentum over the last decade due to the inherent unstable dynamics of the system. Such robots are characterised by the ability to balance on its two wheels and spin on the spot. These have capabilities to solve a number of challenges in society and industry. For example, a motorised wheelchair utilising this technology would give the operator greater manoeuvrability and thus access to places most able-bodied people take for granted. Small carts built utilising this technology allow people to travel short distances in factories or a small area. The robot utilises a Proportional-Integral-Derivative (PID) controlled differential steering method for trajectory control. An indirect Kalman filter configuration combining free scale board with accelerometers is implemented to obtain an accurate estimate of the tilt angle and its derivative. An accelerometer measures acceleration of components that is mounted on it. In sensor world, accelerometer is very important because they can sense a wide range of motion. Accelerometer also detects the angle with respect to gravity. To Balance the left and right motors, two separate H-bridges are used. H-bridge is an electronic circuit that enables the voltage applied across in either direction. Our goal is to control the rotation of the motors in either direction in order to balance the robot.

II. PROPOSED METHODOLOGY

An accelerometer measures acceleration (change in speed) of robot. Inside the MEMS accelerator device, there are tiny micro-structures that bend due to momentum and gravity. When it experiences any form of acceleration, these tiny structures bend by an equivalent amount which can be electrically detected.

Axis of Accelerometer:

The accelerometer can only measure force in a single direction i.e along the axis of acceleration. This mean,s with a single axis accelerometer, you can only measure the force in the either X or Y or Z direction. It is always advantageous to use at least 2 axes accelerometer. We use both X and Y axis to balance the robot and for better result.

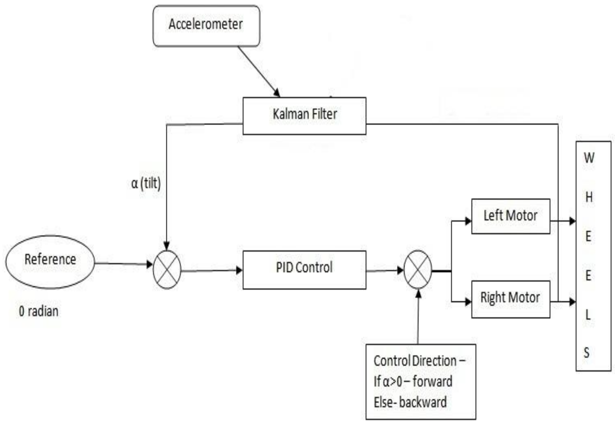

Figure 1: Blockdiagram

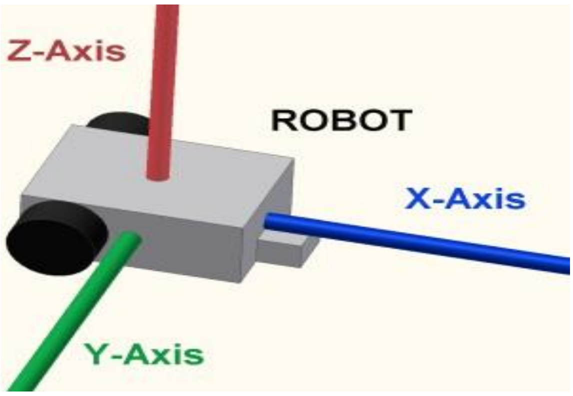

Figure 2: 3-Axis accelerometer

Gravity:

In order to balance the robot, we need to consider the acceleration due to gravity. i.e. -9.81 m/s^2 (-ve means towards the ground). Because of this, robot can detect the angle between direction of motion and the direction of gravitational force. If it is required for robot to be balanced and standing up, simply use a 3-axis accelerometer. As long as the X, Y and Z axes detect zero acceleration, this means your robot device is perfectly still and balanced.

Acceleration and Angle calculation w.r.t gravity

To calculate the magnitude of acceleration:

1-axis accelerometer**:** Max_ acceleration = $\sqrt{x^2}$ = x

2-axis accelerometer: Max_ acceleration = $\sqrt{(x^2 + y^2)}$

3-axis accelerometer: Max_ acceleration = $\sqrt{x^2 + y^2 + z^2}$

To calculate the detected change in motion due to gravity:

Gravity_force = -g*cos(angle) (depends on starting axis of sensor)

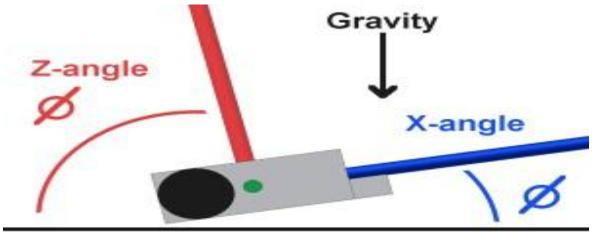

Figure 3: Angle tilt of an accelerometer w.r.t gravity

Here there is no need to measure the force, you can calculate the angle can be calculated by knowing the force in the vertical direction:

cos(sensor_value*conversion_constant / -g)^-1 = angle

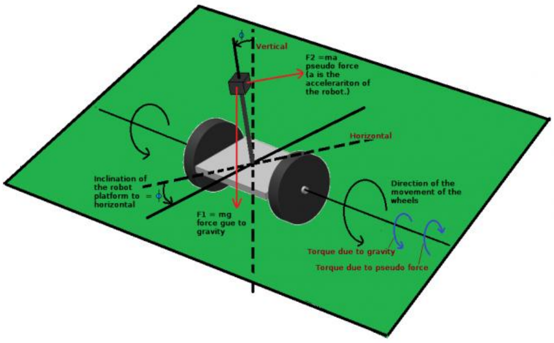

Figure 4: 3 dimensional view of accelerometer working

Analysing the classic inverted pendulum problem is important to design a self balancing robot. The goal of the control feedback loop is to adjust the wheels position so that the inclination angle remains stable at a pre-determined value (e.g. the angle when the robot angle tilt is 0 degree i.e. balanced). When the robot starts to tilt in one direction, the wheels should move in the tilt direction to correct the inclination angle. When the deviation from equilibrium is less, then we should move the motors "lightly" and when the deviation is more, we should move motors at greater speed.

To simplify, we limit the robot's movement to be on a straight line i.e. only to and fro moment and thus both wheel are moved at the same speed in the same direction. With this restriction, the calculation becomes very simple as we only need to think about sensor readings on a single plane. If the robot is allowed to rotate, then each wheel has to be controlled independently. The general principles are same nevertheless but the falling direction of the robot is still restricted to a single plane.

Estimating the Inclination Angle using Accelerometer is required. As mentioned above, we need a good measurement of the current inclination angle in order to control the robot's movements. Let us consider robot to be in a stationary position as given below (accelerometer is placed on top of the robot and perpendicular to the body)

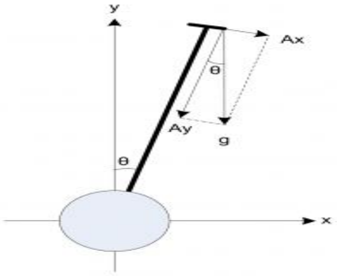

Figure 5: measuring the inclination angle wrt axis

The inclination angle is given by:

$$\theta = tan^{-1}(A_y * A_x) = sin^{-1} A_x (\sqrt{A_x^2 + A_y^2}) = sin^{-1}(g * A_x)$$

Where, A_x is the accelerometer reading in x axis and A_y is the accelerometer reading in y axis. When the robot is stationary, g is the gravitational constant. In the inverted pendulum application, we are only interested in calculations where the inclination angle is small and our goal is to ensure that the deviation from equilibrium is as small as possible i.e. typical equilibrium is reached when the inclination angle is close to 0 (zero) degree depending on the robot weight distribution. So, for small inclination angles that is motion due to vibrations and small motions equations can be modified as :

$$\theta \approx sin(\theta) = g\ A_x$$

By measuring only the x axis of the accelerometer we can get a good estimate of the inclination angle. Of course, this is under the assumption that the robot is in stationary position. And in reality, when the robot is not stationary, it will accelerate towards the direction of tilt and thus the x axis reading of the accelerometer will be slightly more than A_x in stationary position due to the acceleration. At the same time, the y axis reading will be slightly less than the reading in standstill condition (A_y). As a result, the combined vector will deviate from g. But when the accelerometer is placed near the centre of gravity of the robot, the acceleration along the x axis is small in near-equilibrium conditions. So the above equation will exhibit some small error, but it remains a good approximation of the inclination angle. Accelerometer tends to be highly sensitive to the accelerations introduced due to movement or vibration and thus the sensor readings will contain some level of noise, which can be removed easily i.e. To prevent the movement of the robot due to vibrations we are going to smoothening the disturbance in the reading of accelerometer by taking the average of 30 samples. So by relying on accelerometer readings alone, we can get a reliable inclination angle estimate.

Kalman filter:

It is an adaptive filter that can be used to filter the data from accelerometer only. In order to design the optimal Kalman filter, we needed to know the precise underlying model of the system and also there is a need to reliably estimate the noise covariance matrices. Without any reliable information on these parameters, the filter may still work but will not be in an optimal sense. Simpler methods can be used in situations where these parameters are unknown and can still achieve reasonably good result. So, to keep the implementation simple, we used the method illustrated below where the estimated value is measurements from the accelerometer. Each sensor reading is multiplied by a fixed gain: Sensor fusion from the above diagram, we can see that in order to make the accelerometer readings more reliable, the readings are passed through a low pass filter (e.g. averaging over time) to smooth out any sudden change in values. Each coefficient of the filter is given different weight and then added to give the final estimate. Mathematically, the estimated angle can be expressed as follows:

$$\theta_{est}|_{t2}=\alpha(\theta_{est}|_{t1}+\Delta t)+ \beta\theta A_x\alpha+\beta$$

Where angle A_x is the angle calculated from the accelerometer reading shown in equation.

The weights are chosen such that the transient errors in accelerometer measurements do not cause the estimates to vary too much from iteration to iteration. These parameters are sensitive to the sampling period. Accelerometer readings should be given a higher weight (e.g. <0.9) as its angle measurement is used to correct drift. The filtering technique using combination of values from multiple sensors is sometimes casually referred to as complementary filtering, and it is used widely in many data fusion applications. It can be shown that this simple filtering used in this work is a special case of the more generic Kalman filter. The main difference is that, in our implementation the covariance matrix is computed according to the underlying physical process model, the Kalman filter is the optimal choice.

The Control Loop:

In the above section, we have discussed the method for obtaining an accurate inclination angle estimate based on the values provided by the accelerometer. We now need to control the motor accordingly use this estimate so that the robot can remain balanced. The simplest method is to rotate the wheels in the tilt direction until the inclination angle reaches the value at which robot is balanced. Heuristically, the wheel rotational speed should be proportional to the inclination angle (e.g. faster when the angle is larger and slower when the angle is smaller) so that the robot moves smoothly. This technique is effectively implemented simply assuming PID control with both *I* and the *D* terms set to zero. In practice though, a full PID implementation is generally needed to make the inverted pendulum stable.

Then the forward (or backward) acceleration a of the robot can be calculated to

$$a= \pm\sqrt{x^2+z^2-1}$$

- for the case a<0
+for the case a>0
&

$$Tilt=arcsine((x-z*\sqrt{x^2+z^2-1}))/(x^2+z^2)$$

for the case a>0

$$Tilt=arcsine((x+z*\sqrt{x^2+z^2-1}))/(x^2+z^2)$$

for the case a<0

Tilt=arcsine(x)
for the case a=0

All values are normalized to earth's acceleration g (g =1).

In order to find the sign or direction of the acceleration to get the correct result for the tilt. This could be derived from the motor control comparing the motor power during the last two control steps before this measurement. For the motor control, In addition to the tilt, it is then essential to also use the tilt change rate (for a PD regulation) by comparing the last two tilt values (differentiating), because if you use only the tilt itself, the reaction of the motors will be slow. A simple way of doing this could be to work with a running average for the offset. Make a reference measurement of the offset as a starting point and keep the robot in an upright position for a short time after releasing the reset button. Then update the offset with a weighted value of the rate measurement, such as:

offsetnew=offset*(999/1000)+ tilt rate/1000

for every new measurement of the tilt rate. The weighting should be adapted to the timing period of your measurement updates. Assuming a measurement timing period of 10ms (100Hz), the above equation would correspond to a low pass filter with 100Hz/1000=0.1 Hz. Filtering the dc component of the measurement signal to be used for the offset.

In order to prevent movement of the robot due to vibrations, we are going to eliminate the disturbance in the reading of accelerometer by taking the average of 30 samples.

H-bridge: H-Bridge is an electronic circuit that enables the voltage applied across in either direction. This circuit helps to allow the DC motors to run forwards and backwards.

Freedom freescale: Freescale board is a hardware component; it is a latest new technology that we have implemented here. Freescale is very easy to handle and stability is more.

III. RESULT

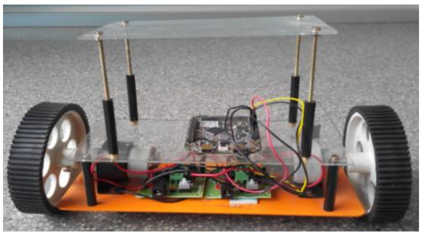

Figure 6: Self balancing Robot without load

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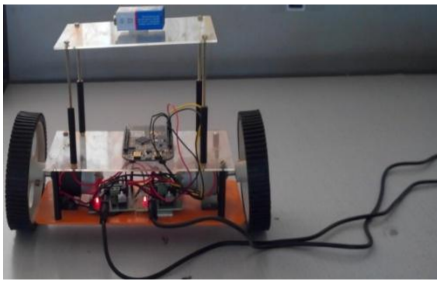

Figure 7: A Self balancing Robot with load

IV. CONCLUSION

This project was successful in achieving its aim to balance a two-wheeled self balancing autonomous robot based on the inverted pendulum model. The control strategy called proportional integral derivative controller to control the trajectory of the robot which calculates an error value.

The Kalman filter has been successfully implemented. An indirect Kalman filter configuration combining freescale board having 3-axis Accelerometer is implemented to obtain an accurate estimation of tilt angle and its derivative with respect to gravity. Usage of the hardware components is minimized and is cost effective. Stability is more compared to the other two wheeled self balancing robot.

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