The Implementation of FPGA Platform for the Motion Control of A Two-Wheel Robot

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Abstract— **This research is trying to control a two-wheeled-driven inverted pendulum using a digital control system implemented by FPGA. This system can automatically be balanced upright driving by a closed loop negative-feedback control. This system integrates a gyroscope and an accelerometer to measure the tilt angular velocity and acceleration of the robot for more accurate motion control. A filter is applied by using sensor fusion technology; that is used to reduce noise caused by many factors. These modules are not only designed to calculate the correct tilt angle for system PID feedback control, but also interfaced by using SOPC design. Due to the use of multiple interfaces, real-time interaction, complicated modular control, and motion planning and controllers in hardware and software design process should have better visualization to support the analysis of the proportional-integral-derivative controller so that the concept of system platform is also applied. The system platform uses PC as the Host to view the messages through mobile system's data connection.**

Keywords—**FPGA; two-wheeled-driven; sensor fusion; PID; system platform; visualization**

I. Introduction

In recent years more people join the related researches and the equipment development of intelligent robot. The manufacturing is reduced gradually on cost and development difficulty, which makes the industry, would like to use various robots. At present, the applications of robot have already expanded in home care, electronics toys, precise medical treatment, engineering, disaster rescue, etc. The development process of robot can be divided into four parts: Motion Control and Planning, Human Machine Interface, Sensing Technology, and Intelligent Interaction. The research of Two-Wheeled Robot includes balance control, action control, orbital tracking and various applications. Those subjects are important researches as the basis of intelligent robots [7].

This research has two main requirements:

First requirement is sensor integration technology to correct inputs from multiple sensors. If two-wheel robot wants to stand, it must use sensors to get its status from Gyroscope, Accelerometer, Inclinometer, etc. Each sensor has its advantages and defects, (i.e., the use Inclinometer can get accurate moving angle), but its response is not quite fast enough. Also Gyroscope can give fast response, but it has problem of signal drift. Before using sensors to get robot's status, one must solve problems from sensors.

The second requirement is using theory of automatic control to maintain upright position, to control moving direction and to adjust speed of rotation of the motor. The control methods can be roughly separated into parts, using mathematical model or not using mathematics to do the motor control. A mathematical model to do the motor control have methods, Lagrange motion equation, State-Space methods for control and Proportional Integral Derivative (PID) [6] [8] [9], etc. In [14, 15], Fuzzy logic can be used in a non-mathematical model to do the motor control.

See World Record Academy of the related research papers that have five paper selectedince 1988, T. Kawamura and K. Yamafuji proposed paper "Postural Control of a mono-axial bicycle" [1]. In 1991, O.Matsumoto, S.Kajita and K.tani used the control method of adaptability control theories, made the two-wheel robot can equilibrium [2]. In 1992, E.koyanagi, S.Iida,K.kimoto and S.tuta used the control method of two-dimensional trajectory , made the two-wheel robot [3]. In 1994, Y.Ha and S.Yuta used the control method of Lagrange motion equation [4]. In 2002, F.Grasser, A.D'Arrigo, S.Colombi and A.C.Rufer used the control method of system's status feedback [5]. The well-known two-wheel robot in commercial applications includes "SegWay" developed by DEKA and "LegWay" developed by LEGO.

II. The Concept of Robot Design

Developing a robot system, there are problems to be faced or solved, as follow:

1. The complexity of multiple input-interfaces for integration.
2. The real-time control of dynamic systems.
3. The wireless data collection.
4. Visibility of system integration.
5. Finding the controller's parameters for system stabilization.

This research of two-wheel robot control system can be divided into four parts:

1. Sensor devices: There are Gyroscope and Accelerometer combined signals applied so that system can get accurate status.
2. Motor control system: In this research, the classic control system in the industry should use adequate control system. According to the input signal from sensing devices to control speed and direction of motors.
3. Motor driver: About this driver, we should use DC motor to get enough power for fast reaction.
4. Debugging supports: This research needs to establish a platform by the connection of PC and FPGA to get visibility for analyzing the control parameters and system performance.

Further more, we use FPGA to do computation to reduce time delay. So, the architecture of SOPC with hardware and software co-design should be also applied [11-13].

III. THE MAJOR COMPONENTS

A. The physical model of two-wheel robot

The Two-wheel robot is fast and unstable nonlinear system, when robot tilt, wheels must be move in a certain speed with the same direction to pull the robot back. It is a feedback control system of a rotary inverted pendulum; this physical model is shown in Fig.1.

B. Gyroscope

From the technology of MEMS, the Gyroscope is a tiny sensor of using Coriolis Effect to measure angle velocity of the moving object. Each axis's angle velocity of three-axis gyroscope has been shown by projection onto signal voltage change. As shown in Fig.2.

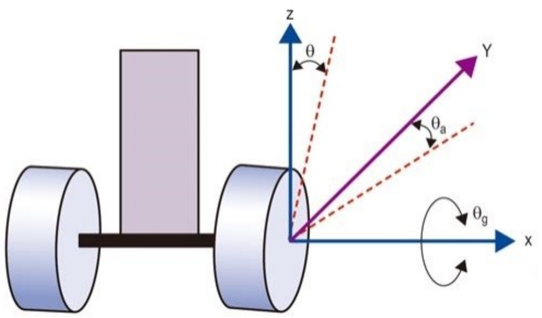


Fig.1 The physical model of two-wheel robot

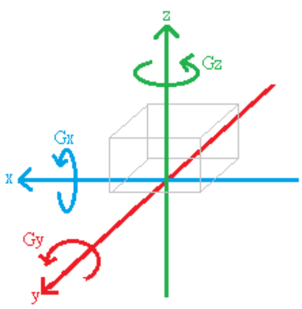


Fig.2 Vector model of gyroscope

From experiments, Gyroscope had floating errors in dynamic and static operations. Therefore, it needs a low-pass-filter to get signal ω_{base}. Then the gyroscope output signal ω_g should adjust from ω_{base} and multiplied by scale factor, and then we can get the angular velocity of this system. And, angular velocity is integrated over time to get the accurate angle. Therefore, the gyroscope's angle calculation is as Equation 1.

$$\theta_g = \sum(\omega_g - \omega_{base}) \times S \times \Delta t \quad (1)$$

Those errors are mainly from voltage drift or sensor's temperature variation. Those errors will be accumulated after a period of time or abrupt change angle.

C. Accelerometer

Accelerometer is also a small module of MEMS and it has flexible circuits to measure acceleration of motion object including parameters of gravity and dynamic acceleration. When motion object has acceleration, the inertial mass of the sensor will deflect inside the chip and cause differential capacitance with respect to the value of balance. Same as gyroscope, it will also make signal change, but in different derivatives. Each sensor has three-axis to measure angle-acceleration, as shown in Fig. 3.

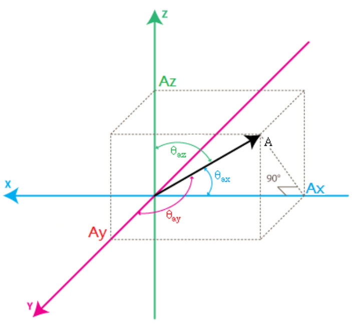


Fig.3 Vector model ofs 3-axis accelerometer

To simplify this research, this two-wheel robot uses x and y-axis of accelerometer. The static acceleration can be acquired through Pythagorean Theorem and Inverse trigonometric functions to calculate the value of tilt angle, as shown in formula 2.

$$\theta_{ay} = \tan^{-1}\left(\frac{a_y}{\sqrt{{a_x}^2 + {a_z}^2}}\right) \times \frac{180}{\pi} \quad (2)$$

However, the dynamic systems have unstable outcome sometime and is called the noise. For the sensing value from dynamic accelerator the most critical problems include the high-frequency noise and non-linear signals. Therefore, it needs to use another sensor to remove such kinds of noise or spike.

D. The driver of motor

For the considerations of the mobility of robot, a powerful DC motor is used. The supply voltage may range from 5v to 12v in this system. The voltage and current of the DC motors are too large for DE0-Nano to provide directly so that additional driving and control circuits have been used. The driving circuits can be divided into two parts, including power switching and speed/direction controls

IV. Design of system

A. The system design

From last section, the 3-axis sensing devices composed of gyroscope and accelerometer. The use of sensing devices in this research is to measure the posture and status of two-wheel robot to maintain the movement of the robot in a set-point, y_s. When the system is working, sensing devices provide the reference value of upright position, y_m, and get the value e by y_m minus the set-point y_s. Then, the control device computes/corrects a value of u as the reference force for driving. Finally, according the reference force value u, the driver provide correlated/smoothing control signal to motor and the structure of this robot is moving which creates a feedback a new y. From sensing device to driver, this system is a close-loop control system; the system block-diagram is shown in Fig.4.

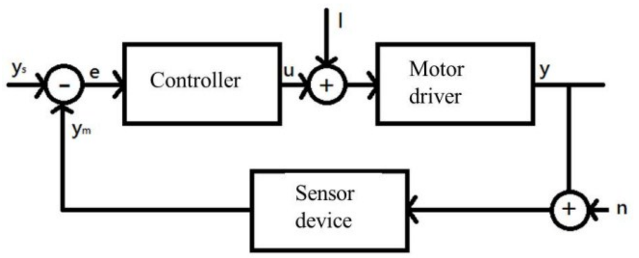


Fig.4 Typical negative feedback closed-loop control system

B. The update frequency of system operation

Today's digital system is discrete and needs longer time to compute accurate output than the analog system. So signal must be taken from each sample, the valid sampling rate is important to system. The sampling cycle time of a system is depending on the time to measure and produce the parameters of controller. If sampling frequency is too fast, it will make system expend too much power and resources to compute and we require an expansive system. In the other way, if cycle time is too long, it will make controller very difficult to control this system with insufficient data.

Normally, sampling frequency is two to ten times higher than the signaling frequency of the object under control. From this research, the observed result in this experiment for sensing device is set to 250HZ and the frequency of the controller and driver are set to 100~150HZ to maintain more smooth movement in performance.

C. Technology of sensor fusion

The sensor fusion means the methods of integration of multiple sensor devices. The purpose of sensor fusion of gyroscope and accelerometer is to get a more accurate posture signal of this robot. The signal measurement is a kind of recursive estimation to predict a value of parameter such as through the computing of weighted average of value. Giving the heavy weighting value to the small error will have very fine observation. Here, the frequently use methods include the use of filters and correlators. We hope that the predictive value of a filter is more close to the true value. For simplification of system design, it is best that the filter only needs the last predictive value to measure the current value at present. Fortunately, a filter named Kalman filter meet the requirements. The Kalman filter doesn't need records of a large number of predictive and measured values. The other advantage of Kalman filter is that it doesn't need to transfer to frequency domain using too much resource.

Kalman filter is based on Linear Algebra with Hidden Markov models [10]. Robot system is a basic dynamic system and can be denoted by a Markov chain. The Markov chain is based on a linear equation of interfere with Gaussian noise. System's status can be denoted by a vector of real number. Within the discrete time system, this linear equation will be acts on the current state of system to create a new parameters/status. At the same time, some control signal of controller be added and the other linear equation of interfere with noise will be considered to create outputs of those hidden states.

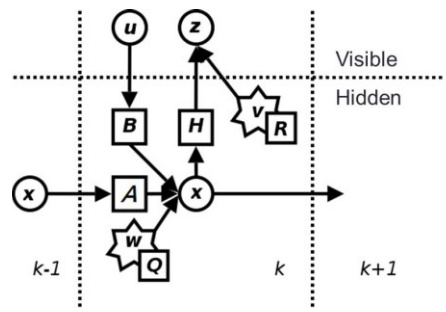


Fig.5 Architecture of Kalman filter

In order to estimate the internal state of the process of measurement by Kalman filter, we must build model under the framework of Kalman filter algorithms. It needs to define array of A, H, Q and R, B for every step K. In Kalman filter, the predicted k will be evaluated from the k-1. The status x and z in K is measured as shown in formula 3:

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1}$$
$$z_k = Hx_k + v_k \tag{3}$$

An array A in formula 3 acts as the status mode change of x_{k-1}. State without any drive function or noise in process, the A has been denoted the last value in k-1 and to be used in step k. B is also an array, it acts on the input mode control of vector of u_{k-1}. The input control u is applied to status x directly. An observation model array H is mapped to the real status space. w_k and v_k are noises of process and noise of measuring respectively, and there average value are zero. The covariance matrixes Q and R are independent and normal distribution, as shown in formula 4.

$$p(w) \sim N(0, Q) \qquad p(v) \sim N(0, R) \tag{4}$$

Base on this linear dynamic system, that the main matrixes of A, B and H are constant. For simplicity, we suppose that the covariance matrix Q and R be constant too. Then, the Kalman gain K_k will weight to measuring value at every step to get the minimum error of each covariance matrix P_k. Therefore, the values of upgrade status will be accurate and sensitive.

This research uses the above theory to balance the robot. The first step is building on the status and measuring value from formula 3. Obviously, the tilt angle θ has to be estimated by the gyroscope data, deviation ω_{x0}. For the purpose of correlation it also needs the accelerometer to measure tilt, so that it can limit drift error in tilt angle. Therefore, we can set $b = \omega_{x0}$ and deviation of gyroscope data as constant, we can set the measuring value ω_x of gyroscope as the input value u_k. Then, formula 3 can be rewritten as formula 5.

$$\theta_{g\_k+1} = \theta_{g\_k} + \omega_{g\_k+1} \cdot \Delta T - b \cdot \Delta T \qquad b = \omega_{g\_base} \tag{5}$$

According to formula 3, the measuring value is as formula 6.

$$z_k = \theta_{ay\_k} \tag{6}$$

Combine formula 5 and 6, formula 3 can build the formula 7. For formula 7, we can find matrix A, B and H.

$$x_{k+1} = \begin{bmatrix} \theta_{g\_k+1} \\ b_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & -\Delta T \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \theta_{g\_k} \\ b_k \end{bmatrix} + \begin{bmatrix} \Delta T \\ 0 \end{bmatrix} \cdot u_k \tag{7}$$

$$z_k = [1 \quad 0] \cdot \begin{bmatrix} \theta_{ay} \\ b_k \end{bmatrix} \tag{8}$$

Next, we can find the covariance matrix of process and measurement, Q and R, from the offline experiments.

$$R = E(z_k z_k^T) \approx \sigma(\theta_{ay\_k})$$

$$Q = E(x_k x_k^T) = \begin{bmatrix} E(\theta_{g\_k}\theta_{g\_k}^T) & 0 \\ 0 & E(b_k b_k^T) \end{bmatrix} \approx \begin{bmatrix} \sigma(\omega_{g\_k}) \cdot \Delta T^2 & 0 \\ 0 & \sigma(b) \end{bmatrix} \tag{9}$$

Furthermore, the Kalman filter algorithm is shown in Fig.6. Suppose the first values are X0 and P0. Kalman filter algorithm can be divided into two: the predict part and correct part. Predict part is mainly use the last predict value to compute the new predict value. Correct part in filter is used to get a more accurate predict value.

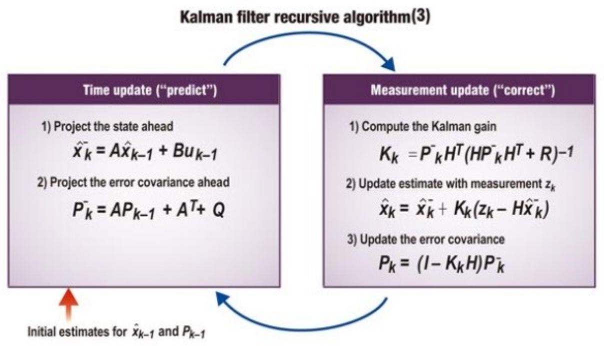


Fig.6 Algorithm of Kalman filter

Finally, to test the performance of Kalman filter, we should make sure the tilt angle is accurate and without drift because gyroscope's deviation has been optimize estimate in circuit. This system must keep adjusting the Kalman filter parameters Q and R matrices continuously.

D. The design of PID controller

Although PID control theory has developed over one hundred years, it is still the common method of control in industry. The structure of PID is simple and easy to implement with good effect. Therefore, PID controller is used to control the two-wheel robot in this research. PID controller can be applied to dynamic time-invariant systems. PID controller has three major factors in algorithm, and its architecture is shown in Fig.7.

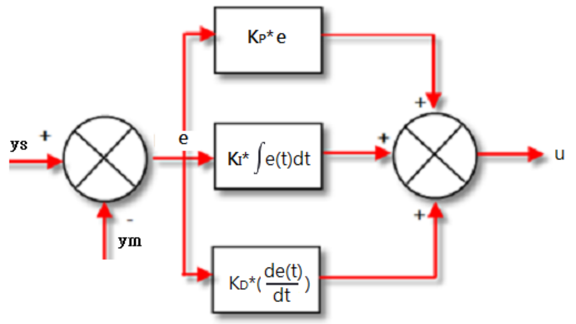


FIg.7 Architecture of PID

Those three kind algorithms can be added to adjust parameters of control. There are negative values added so that the control system is called a negative feedback control system. As shown in formula 6.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau\,(t) + K_d \frac{de(t)}{dt} \tag{6}$$

Proportional only can work when controller output is proportional to system error value. Integral function has delay factors for correction. Integral continuously accumulated error value of past time and multiply by integral constant K_i. Derivative function has advanced information to predict the value for correction. The design of PID controller is finding right parameters K_p, K_i and K_d.

The adjusting of parameters can be divided into two parts:

First, the theoretical method of adjustment is invalid. According to math model and method of control theory, the process is rigorous and the calculation process is cumbersome with excessive reliance. The parameters may not be acquired directly; it still has to be adjusted from the experiment.

Second, the engineering tuning of parameters is important. The method of engineering tuning is simple, useful, easy to apply.

In fact, we found useful way to get the parameters, and we use the method of engineering parameter tuning to adjust parameters in this research.

E. Design of driving circuit of motor

The DC motor supply voltage input range is 5v to 12v for flexible control experiment; however, this kind of power may not be supplied or provided by DE0-Nano. Additional drive circuits to interface with motor, this drive circuits can be divided into two parts:

First part is amplification circuits outside the FPGA; it composes to two groups of Darlington circuits with two inputs each to control speed and direction. The Darlington circuit is shown in Fig. 8.

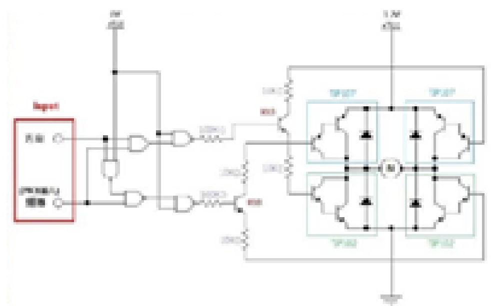


Fig.8 Design of Amplifying circuit

Second part is PWM circuit inside the FPGA or DE0-Nano. Since a digital system has the presentations of 0/1 or on/off only. So, the analogue value must be converted into time period or call the method of pulse width Modulation (PWM). The PWM signal is using the correlated results of PID controller to give the proportional width of the pulse signal to control motor. Positive and negative of control value decides the direction of motor, as shown in Fig. 9.

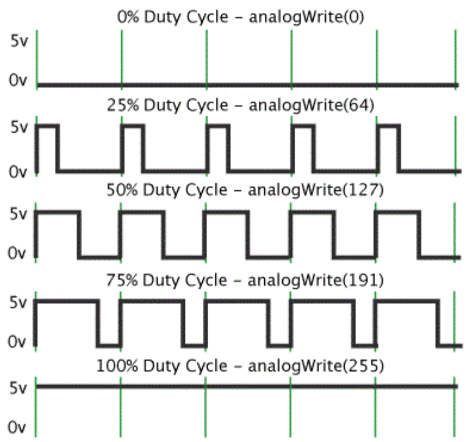


Fig.9 Control signal of PWM

V. Experiment and Analysis

A. System analysis

This research is trying to design and control a dynamic system, its main problem is that the time delay and smooth control for fast feedback with appropriate control. These delays can cause the signal processing resonance (damping/over damping). Based on the experiences before, we have to face the problems, and one should work out to find the practices in many situations effectively. We have good experiences in use of the FPGA in design, testing and integration.

From very beginning of the development stage, a concept of using platform is decided. This platform is using the FPGA as the center core with NOIS processor with powerful support of the software so that this research uses a communication interface between PC and FPGA for in-depth system verification and analysis. The two wheel-robot system architecture is shown in Figure.10.

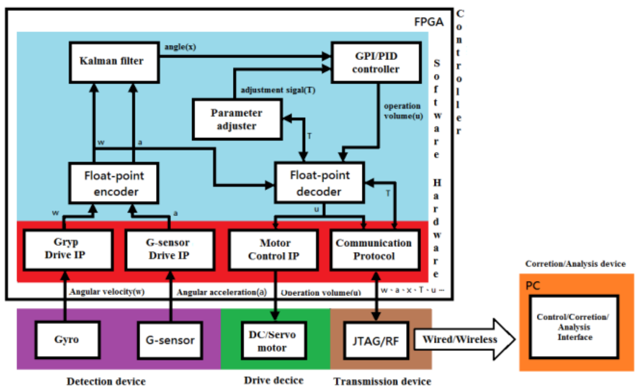


Figure.10 System architecture consists of FPGA, peripheral and PC

B. Sensor Analysis

In beginning of the experiment, the first operation of this system is to get the gyro's voltage of initial/upright position at idle/static stage for a short period of time. Since two-wheel robot is tilted around the x-axis in gyroscope, there is no need to measure the other axes signals. Gyro angular velocity of the x-axis output signal of the angle as shown in Fig.11, is appear from the static-state to the state with angular velocity. It can be found that this system has idle for a period of time and move thereafter. The calculated angle has integral drift phenomenon. Gravitational acceleration measurement is measured which is different from the gyro that needs to calculate the average signal. Because the use of trigonometric calculations tilt angle, one needs to do three-axis calculation. One the other hand, The accelerometer gauging provide the gravity acceleration, therefore there is not need to calculate the average signal.

(a)

(b)

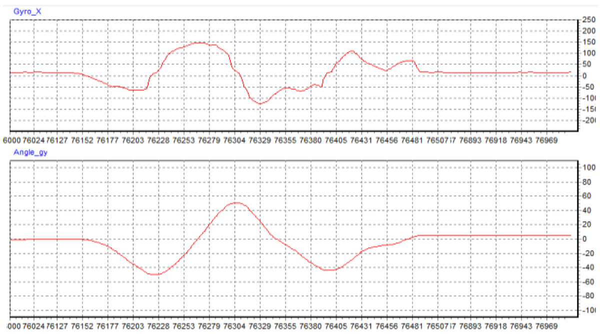


Fig.11 (a) gyroscope angular and (b) angle

The output of each axis accelerometer signals is shown in Figure.12. Since two-wheel robot is tilted axis accelerometer xy plane, so the x-axis will not have a significant change. But from the figure, one can find many different sizes of glitches; these are treated as noise in the system in dynamic acceleration.

Thus, in the previous analysis, the sensor composed of single sensing device and the result has the signal drift or float defects. So, the sensors require integration technology with be able to obtain compensation for accurate signal. This system uses a Kalman filter to achieve this purpose.

(a)

(b)

(c)

(d)

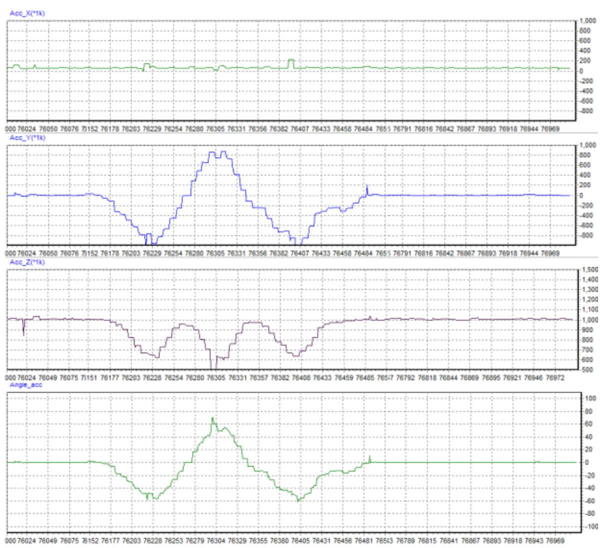


Figure.12 triaxial accelerometer acceleration and angle after conversion (a) x-axis (b) y-axis (c) z-axis (d) the inclination angle

Gyroscopes and accelerometers calculated by the Kalman filter for the signal shown in Fig.13. Kalman filter will be used to correct the signal of the accelerometer gyroscope signal. one can see from the top through the Kalman filter correction signal retained from the rate gyro, and this signal has no drift.

(a)

(b)

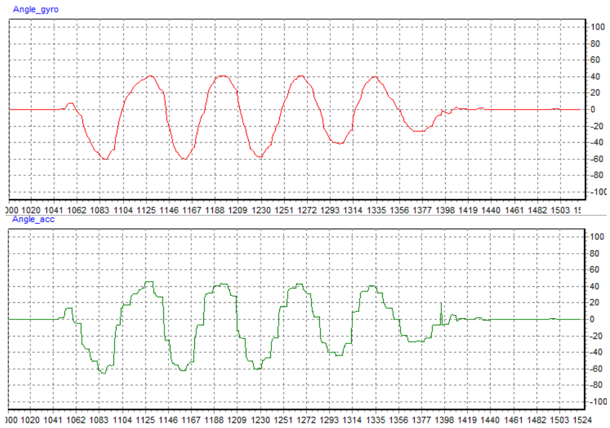


Fig.13 angle after the Kalman filter by signal (a) a gyro compensated inclination angle (b) accelerometer tilt angle

C. Controller Analysis

The study of this controller should be focused on balancing function of two-wheel robot. The control system is very important, especially for the correction control in real time. The method of adjust control parameters is using Ziegler-Nichols method. By observing the output of the sensing devices, the tilt angle of the control is use to check performance of control system. On the other hand, according to the signal at the frequency of oscillation crossing zero point is used to determine the agility and variation of the system. And then, one may obtain the statistical standard deviation to determine whether the controller parameters are optimal.

PID control uses Z-N adjustment method to decide the parameters, and then start from the proportional adjustment, the robot's posture information is collected with integral term adjustments, until you find the minimal statistical results with the smallest standard deviation parameter.

TABLE 1.
ANALYSIS OF THE PROPORTIONAL CONTROLLER

	$k_p = 1$	$k_p = 2$	$k_p = 3$	$k_p = 4$
VAR	1508.207	1010.532	1132.438	812.6846
STDEV	38.83564	31.78887	33.65172	28.50762
Freq	9	19	22	25
MAX	75.421	60.94	58.729	58.633
MIN	-60.157	-58.729	-60.94	-54.242

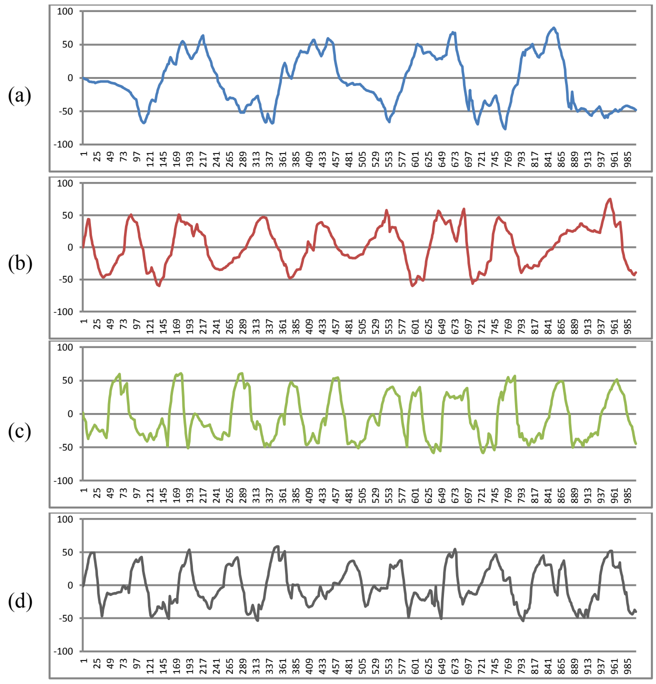


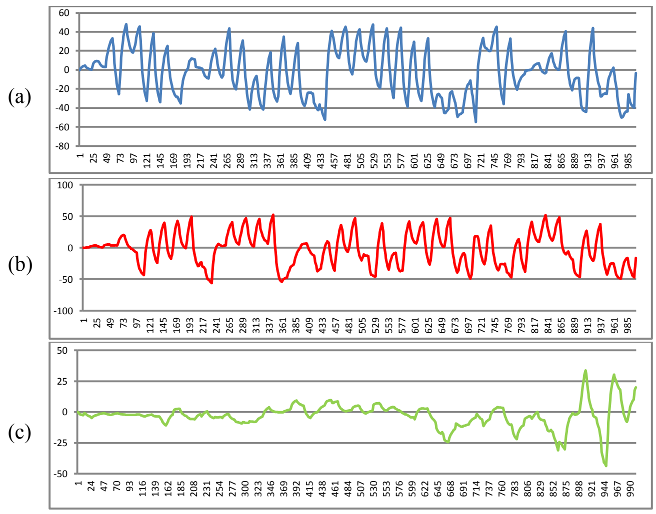
Figure.14 angle signal using a proportional controller (a)Kp=1 (b)Kp=2 (c)kp=3 (d)kp=4

In order to improve the static controller performance, reducing the static error, one should improve the system's steady-state error coefficient, and increase the system's open-loop coefficient. According to Table 1 and Figure.14 the proportional parameter analysis shows that the scale factor k_p increases and the system's response speed will be increase. However, large k_p but will make the system steady-state output increases, and causing the reaction too fast and increase the chances of overshoot. As a result, $k_p = 4$, is a good response speed with smaller swing amplitude.

TABLE 2

PROPORTIONAL - DERIVATIVE CONTROLLER ANALYSIS

	K_d=1.25	K_d = 1	k_d = 0.75	k_d = 0.5
VAR	591.7423	659.5406	87.62004	59.39357
STDEV	24.32575	25.68152	9.360558	7.706723
Freq	47	37	25	32
MAX	48.106	52.085	33.794	19.582
MIN	-54.916	-56.53	-43.816	-22.486



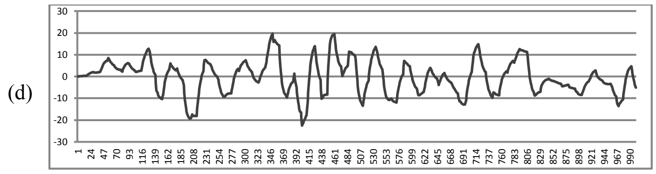


Figure.15 using proportional - derivative controller angle signal (a)Kd=1.25 (b)Kd=1 (c)kd=0.75 (d)kd=0.5

The differential term in this control system is a correction parameter to improve the reaction rate of the system. Observe the differential signal of this system, if the slope of this signal indicates a substantially larger swings, the control should give this differential term is a reduced value of reversing adjust. From Table 2, Figure.15, the adjustment for differential term analysis, when k_d value increases, the reverse of the output also increases. Also, if the value is too large it will make the system overshoot. As the result, the more the contrary k_d, the smaller system output in the reverse direction of force so that the smaller, $k_d = 0.5$ makes the system having a better response speed with smaller swing amplitude.

TABLE 3

PROPORTIONAL - INTEGRAL - DERIVATIVE CONTROLLER ANALYSIS

	k_i = 10	k_i = 20	k_i = 30	k_i = 40
VAR	124.5153	250.279	108.0996	289.0899
STDEV	11.15864	15.82021	10.3971	17.00264
Freq	15	17	27	25
MAX	37.067	37.537	22.979	55.621
MIN	-49.325	-58.222	-32.153	-40.986

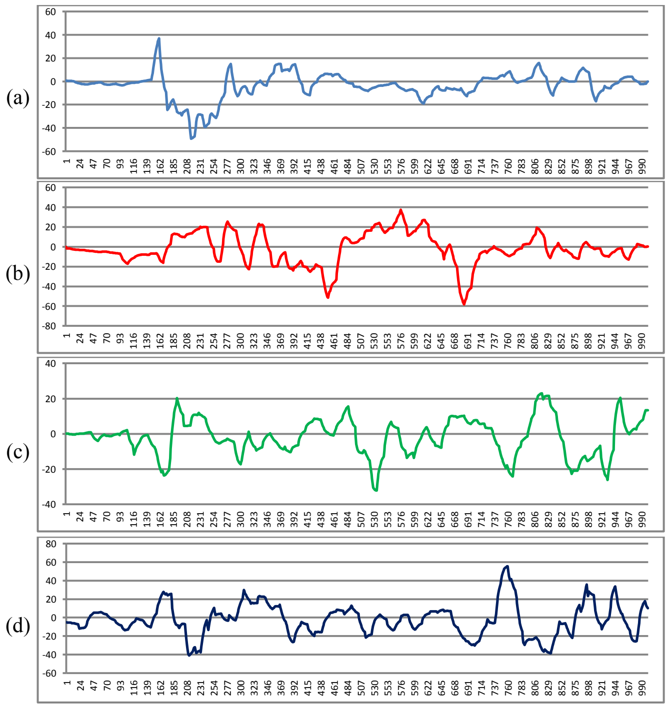


Figure.16 proportional - integral - derivative controller angle signal (a)Ki=10 (b)Ki=20 (c)ki=30 (d)ki=40

The proportional term in the analysis controller, k_p, has positive response. When steady-state output increases, the system will also increase the vibration. It affects the dynamic performance, so that we adjust it to stabilize the output of the integral term to a desired value. With the error accumulated, it will gradually make the output increase. If we increase the coefficient k_i it will affect the system's static performance. It also make the system response is slow. From Figure.16, it shows that the smaller integral term, such as k_i = 10 and 20, k_i, the system takes longer to reach a turning point, and k_i = 40, the system is more instead.

VI. CONCLUSION

This study uses Altera's FPGA, an embedded systems development board DE0-Nano by Terasic, as the core platform to integrate with other hardware peripherals, such as gyroscopes, accelerometers, RS-232, RF chip and DC motors ... and so on, In this paper, the effective use of SOPC design approach combines hardware in high speed performance and software for complex decision functions, and using the PC interfaces for data collection and analysis work to analyzed the performance of the system parameters on the platform. The use of FPGA as the core and good visualization from PC can appropriately analyze the system and successfully fabricated a two-wheeled inverted pendulum robot. This robot is to build full system out of thin air with analyzing support; it can automatically to maintain upright posture with real-time dynamic control.

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