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Design of FPGA-based All Digital PID Controller for Dynamic Systems

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Abstract: In this paper implementation of All digital PID controller using Field Programmable Gate array (FPGA) is presented. Nowadays embedded control applications requires low power and fast acting PID controllers with a closed loop performance using less resources, resulting in cost reduction. In digital PID controller error signal is generated by using comparator which is analog in nature. By using ADC it is converted in to digital. Digital output of FPGA is converted in to analog signal to drive any system using DAC, but potential output ripple in the baseline system due to quantization and other related errors. There is no need to use ADC or DAC in ADPID. The controller algorithm is synthesized, simulated using Xilinx Spartan3e XC3S100E board with XilinxISE 10.1i as a tool.

Keywords: FPGA, ADPID, ADC, Verilog

I. Introduction

The development of PID (Proportional-Integral-Derivative) control theories has already 60 years so far, PID control has been one of the control system design method of the longest history. However, this method is still extensively used now [1, 2]. PID-controller and its modifications are the most common controllers in the industry. It is robust and simple to design, its operation is well known, it has a good noise tolerance, it is inexpensive and it is commercially available [2].

Implementation of digital PID controller has gone through several stages of evolution, from the early mechanical and pneumatic designs to the microprocessor based systems but these systems have the drawback of demanding control requirements of modern power conditioning systems will overload most of the microprocessors and the computing speed limits the use of microprocessor in complex algorithms.

Microprocessors, Microcontrollers and Digital Signal Processors (DSPs) can no longer keep pace with the new generation of applications that requires more flexible and higher performance without increasing cost and resources. Furthermore the tasks are executed sequentially which takes longer processing time to accomplish the same task in Microcontrollers and DSPs. Recently, Field Programmable Gate Arrays (FPGA) has becoming alternative solution for the realization of digital control systems. The FPGA based controllers offer advantages such as high speed computation, complex functionality, real time processing capabilities and low power consumption [3]. In this paper we consider All digital PID controller and is implemented in a dedicated FPGA. Following the standard digital design practices, the controller functionality is described in Verilog. Using synthesis tool, the design is then targeted to the FPGA board.The FPGA is a superior alternative to mask programmed ASICs. FPGAs avoid the high initial cost, the lengthy development cycles, and the

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inherent inflexibility of conventional ASICs. Also, FPGA programmability permits design upgrades in the field with no hardware replacement necessary, an impossibility with ASICs. Section II give structure of PID controller, Section III includes advantages of FPGA based system, Section IV and V give basic idea about Digital systems and ADPID controller and Section VI application of PID controller.

II.PID Controller

PID control, shown in fig. 1, is one of the earlier control strategies .

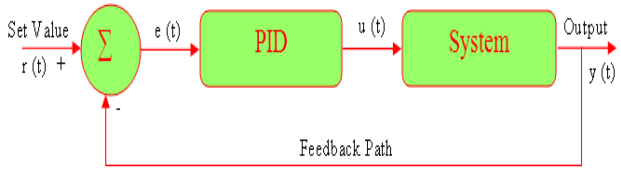

Figure 1 Block diagram of simple PID feedback control system

Its early implementation was in pneumatic devices, followed by vacuum and solid state analog electronics, before arriving at today's digital implementation via microprocessors or FPGA. It has a simple control structure which was understood by plant operators which they found relatively easy to tune. Since many control systems using PID control have proved its satisfactory performance, it still has a wide range of applications in industrial control [8] and it has been an active research topic for many years. Mathematically,

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(t)d\tau + T_d\frac{de(t)}{dt}\right) \quad ..(1)$$

III. Advantages of FPGA based Designs

Field Programmable Gate Arrays (FPGA) has become an alternative solution for the realization of digital control systems, previously dominated by the general-purpose microprocessor systems [4,5]. The FPGA-based controllers offer advantages such as high speed, complex functionality, and low power consumption. These are attractive features from the embedded systems design point of view. Previous work has reported the use of FPGAs in digital feedback control systems such as magnetic bearings, PWM inverters, induction motors, AC/DC converters, variable-speed drives, and anti-windup compensation of controllers.

FPGA offers the most preferred way of designing ADPID controller for temperature control application. They are basically interconnection between different logic blocks. When design is implemented on FPGA they are designed in such a way that they can be easily modified if any need arise in future. We have to just change the interconnection between these logic blocks. This feature of Reprogramming capability of FPGA makes it suitable to make your design using FPGA. Also using FPGA we can implement design within a short time. Thus FPGA is the best way of designing digital PID controller. Also implementation of FPGA-based digital control schemes proves less costly and hence they are economically suitable for small designs.

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IV.Digital control system

In today's scenario of globalization the implementation of production innovation and highly stable operation is the main objective of the process industry in Japan. A recent survey [2] shows that the ratio of applications of PID control, conventional advanced control (feed forward, override, valve position control, gain scheduled PID, etc.) and model predictive control is about 100:10:1.One important activity is improvement in the control performance of PID control systems. The aims of this improvement activity in which controllers are retuned appropriately are [2].

1) To realize stable operation by reducing the influence of disturbances
2) To realize automatic rapid transition of operating conditions such as production rate.
3) To gain the ability to achieve economical operation.
4) To allow operators to be released from taking care of PID controllers.

Obviously, modern advanced control plays an important role to achieve this target but it is emphasize that a key to success is the maximum utilization of PID control and conventional advanced control. The digital Proportional Integral Derivative (PID) controller is one of the most common types of feedback controllers used in dynamic systems. This controller has been widely used in many different areas such as aerospace, process control, manufacturing, robotics, automation, and transportation systems. Implementation of PID controllers has gone through several stages of evolution from the early mechanical and pneumatic designs to the microprocessor based systems.

A. Identify Problem Category of analog PID based controller

This is the first step in which consider whether evaluation involves an existing analog PID controller problem or one that could result from a new design or from proposed changes to the system. In addition different factors are involves for decide the accuracy and stability problem Category like, overshoot, steady state error, internal noise of analog component, signal distortion.

B. Evaluate Solution

Solutions that are not technically viable get thrown out, and the rest of the alternatives are compared on an economic basis. Digital PID based control system consist of ADC at input side to convert comparator based generated error signal in to digital signal. This digital signal is process by FPGA. Digital output signal from FPGA is given to DAC. Which converts digital signal in to analog to drive any system like speed control of DC motor, liquid level control in tank, temperature control, flow control of valve etc. in automation industries.

C. Evaluate Solution

One concept in digital PID based control system consist of ADC at input side to convert error signal in to digital signal and DAC at output side to convert signal in to analog to drive any system like speed control of

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DC motor, liquid level control in tank, temperature control, flow control of valve etc. in automation industries. Another concept is instead of converting error signal in to digital using ADC, convert incoming input signal in to frequency which is basically a digital signal using 555 timer. So in this concept we do not require ADC as well as DAC which can be costly and may introduce error and delay into the system and this system is known as ALL DIGITAL PID CONTROL SYSTEM (ADPID).

V.All Digital PID Controllers

To design an ADPID requires the knowledge to generate a proportional digital signal of the error, an integral digital signal for the errors over time, and a derivative digital signal for the change in error. These three separate signals need to be combined together to form a PWM control signal. An ADPID is mainly constructed by digital logic devices, such as 4-bit up/down counters, JK flip-flop, D flip-flop, multiplexer, and digital gates (*i.e.* AND, OR, EXOR…). In general, the error between the reference and encoded output is counted up or down by counters. The speed of counting depends on frequencies f_P, f_I and f_D. Then, the summation of the counters is counted to zero at frequency f_A. The control signal generated by an ADPID is in PWM form, and the corresponding direction is determined by the most significant bit of the adders.

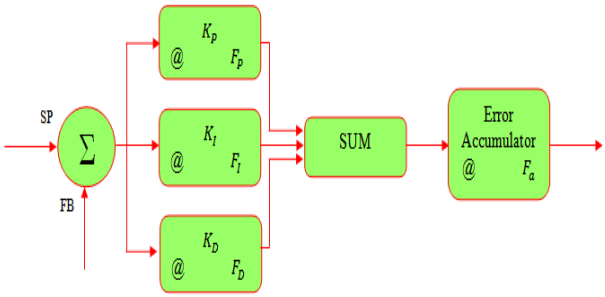

Figure 2 Block Diagram of ADPID

It is totally frequency base method of PID control. The gain of the P, I, D term can be adjust by simply setting the appropriate frequency of the counter for the P, I, D term and the frequency of the final summation counter[7].

The gain of the Proportional K_P , integral K_I and derivatives K_D are define by using the frequency of the counters.

$$K_P = \frac{f_P}{f_A} \quad \ldots.(2)$$

$$K_I = \frac{f_I}{f_A} \quad \ldots.(3)$$

$$K_D = \frac{f_D}{f_A} \quad \ldots(4)$$

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The base frequency, f_A, is the counting frequency for the combined counters. It is directly related to f_P, f_I and f_D. It can be determined after any one of the proportional, integral or derivative frequencies is known. Technically, low frequencies cause inaccurate counting, whereas extremely high counting frequencies create problems such as integrator windup. As a result, more hardware is needed to prevent counting overflow. Hence it is crucial to design a proper counting frequency, to obtain an accurate model yet reduce the hardware to the minimum.

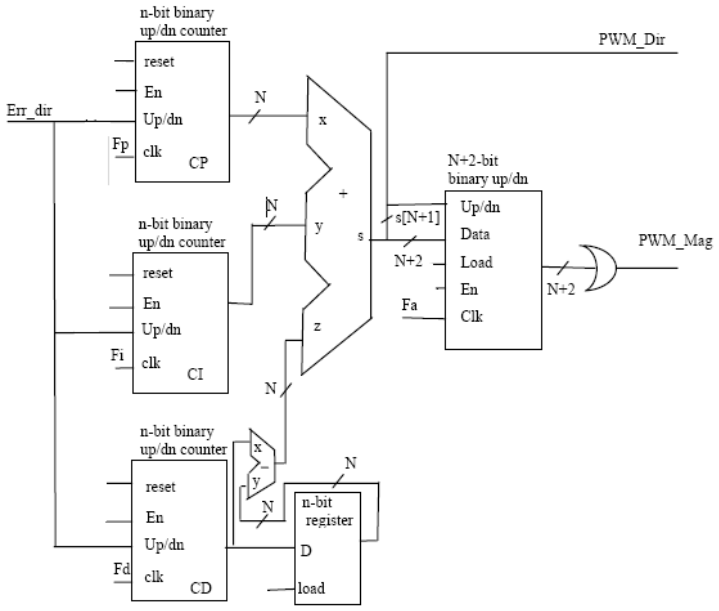

Figure 3 Basic structure of ADPID

1.Error signal

To generate the error signal we need the reference signal and the feedback signal from the system. By comparing these two signals we can generate the error signal.

A. Generate Reference signal

Generated reference is a set of pulse trains that represents the desired output of the encoder. The resolution of the encoder used in the system determines the frequency of the pulses. For example, if a linear encoder represents 1 Volt with one hundred and fifty pulses, the frequency of the reference will be the desired voltage multiplied by one hundred fifty. The conversion from analog voltage to digital pulse train can be done by crystal, 555 Timer, or a Voltage-Controlled-Oscillator (VCO).In our application we use timer 555 timer to generate the reference signal.

B. Feedback Signal

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Feedback signal is the raw system output transformed into digital pulses by an encoder. Among the many encoders, encoder strips and encoder disks are commonly installed in systems. In our system we use the encoder disk which is mounted on the motor shaft. The disc passes through the opto-coupler and gives the train of pulses.

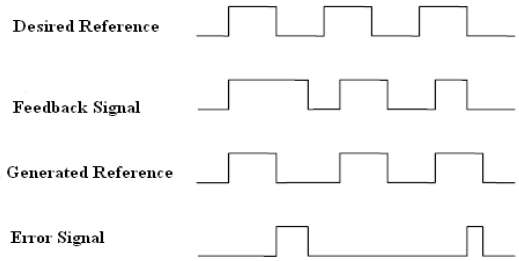

Figure 4 Pulse train of desired output, system output, error, error magnitude and error Direction signals

Table 1 Summary of proportional counting action

Generated Reference	Feedback Signal	Error	Error Direction
0	0	0	0
0	1	1	1
1	0	1	0
1	1	0	0

2. All Digital PID signal

An all digital PID signal composed of mainly three terms:

1) Proportional Error signal
2) Integral Error signal
3) Derivative Error signal

*Addition of the three terms (***P, I, D***)*

As the error signal transitions from high to low, the count-down counter (*CA*) loads the results from the adder (*CP+ CI + (CD-R)*). The counting direction depends on the result from the adder. If the most significant bit (MSB) of the adder is "1", the summation of the three terms is negative; thus the combined counter will count up at frequency f_A to zero. On the other hand, if the MSB of the adder is "0", the summation of the three terms is positive; then the combined counter counts down at frequency f_A to zero. However, the counting sequence is interrupted when load is activated. In this case, the combined counters discontinue the previous counting and pick up the new loaded number.

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The whole logic operation of the combine counter is summarized in the below truth table with respect to the state of error signal and MSB of the summation.

Table 2 Summary of combine counting action

Error	MSB from	Operation of combine counter
0	0	Load the summation from the adder and
0	1	Load the summation from the adder and
1	0	Continue countdown if zero is not reached
1	1	Continue count up if zero is not reached

VI. Proposed design of combine PID

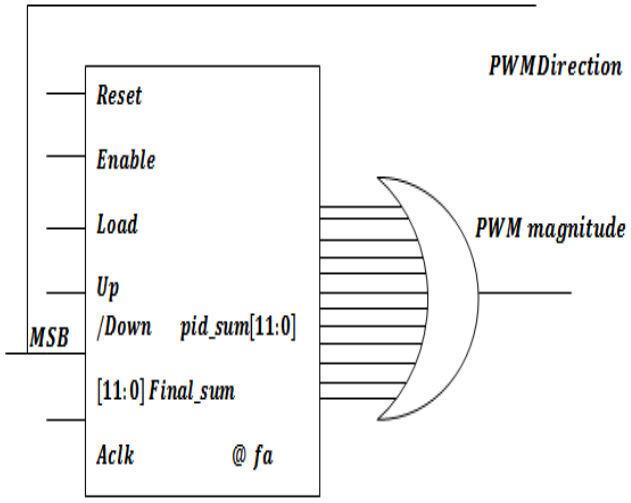

Figure 5 Proposed design of 12 bit combine up/down counter

VII.Proposed System architecture

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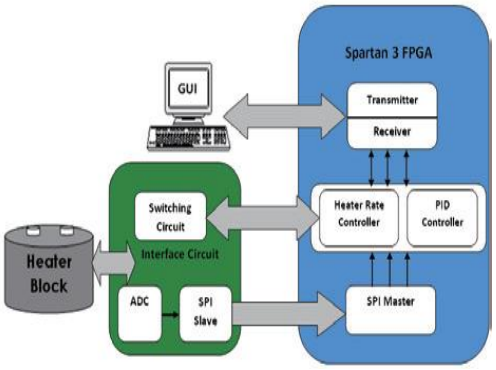

Figure 6 Proposed System architecture

Proposed architecture is shown in Fig. 6

VIII.Conclusion

There are lots of research is going on PID implementation using FPGAs.PID is mostly used controller in industry from last several years. FPGAs are reconfigurable device which can be programmed by user as per their need, so this advantage is very useful for online tuning of the PID while implementing it on FPGAs. All Digital PID is the new aspect in the industrial controller. It is totally base on the frequency. The row data from the system can be directly given to the system and the controller's output can directly given to the system. This avoids the use of analog to digital converter, Which reduce the error and the cost of the system design.

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Biography

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