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Contents

Volume 114
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Editorial

Sensors: Smart vs. Intelligent

Sergey Y. Yurish..... 1

Research Articles

Novel Sensors for Food Inspections

Mohd. Syaifudin Bin Abdul Rahman, Subhas C. Mukhopadhyay and Pak Lam Yu 1

A Neural Network Approach to Fluid Level Measurement in Dynamic Environments Using a Single Capacitive Sensor

Edin Terzic, Romesh Nagarajah, Muhammad Alamgir 41

Novel Orthogonal Signal Based Decomposition of Digital Signals: Application to Sensor Fusion

Abdul Faheem Mohed, Garimella Rama Murthy and Ram Bilas Pachori 56

A Multiobjective Fuzzy Inference System based Deployment Strategy for a Distributed Mobile Sensor Network

Amol P. Bhondekar, Gagan Jindal, T. Ramakrishna Reddy, C. Ghanshyam, Ashavani Kumar, Pawan Kapur and M. L. Singla 66

A Low Cost and High Speed Electrical Capacitance Tomography System Design

Ruzairi Abdul Rahim, Zhen Cong Tee, Mohd Hafiz Fazalul Rahiman, Jayasuman Puspanathan . . 83

Fiber Optic Long Period Grating Based Sensor for Coconut Oil Adulteration Detection

T. M. Libish, J. Linesh, P. Biswas, S. Bandyopadhyay, K. Dasgupta and P. Radhakrishnan 102

Type Identification of Unknown Thermocouple Using Principle Component Analysis

Palash Kundu and Gautam Sarkar..... 112

A Dynamic Micro Force Sensing Probe Based on PVDF

Qiangxian Huang, Kang Ni, Nan Shi, Maosheng Hou, Xiaolong Wang..... 122

LED-Based Colour Sensing System

Ibrahim Al-Bahadly and Rashid Berndt 132

Design and Development of Black Box for Analyzing Accidents in Indian Railways

Alka Dubey and Ashish Verma..... 151

Use of the Maximum Torque Sensor to Reduce the Starting Current in the Induction Motor

Muchlas and Hariyadi Soetedjo..... 161

Implementation of FPGA based PID Controller for DC Motor Speed Control System

Savita Sonoli, Nagabhushan Raju Konduru..... 170

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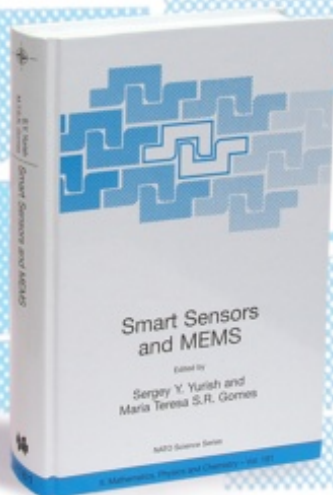
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Implementation of FPGA based PID Controller for DC Motor Speed Control System

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Abstract: In this paper, the implementation of software module using 'VHDL' for Xilinx FPGA (XC3S400) based PID controller for DC motor speed control system is presented. The tools used for building and testing the software modules are Xilinx ISE 9.2i and ModelSim XE III 6.3c. Before verifying the design on FPGA the complete design is simulated using Modelsim Simulation tool. A test bench is written where the set speed can be changed for the motor. It is observed that the motor speed gradually changes to the set speed and locks to the set speed. *Copyright © 2010 IFSA.*

Keywords: Field programmable gate array (FPGA), Proportional-integral-derivative (PID) controller, Very high speed integrated circuit hardware description language (VHDL), Pulse width modulation (PWM)

1. Introduction

Hardware Description Languages (HDLs) are used to describe hardware for the purpose of Simulation, Modeling, Testing, Design, and Documentation of digital systems. The most popular HDLs are VHDL [(Very High Speed Integrated Circuit) Hardware Description Language], and Verilog. VHDL can be used to describe hardware from the abstract to the concrete level. Many of the Electronic Design

Automation (EDA) vendors are standardizing on VHDL as input and output from their tools. These tools include simulation tools, synthesis tools, layout tools, testing tools.

The Proportional-Integral-Derivative (PID) controllers have been widely used over the past five decades due to their simplicity, robustness, effectiveness and applicability for a broad class of systems. Despite the numerous control design approaches that have appeared in the literature, it is estimated that, nowadays PID controllers are still employed in more than 95 % of industrial processes [1].

The digital PID controller has been used extensively in real time digital control for many decades, The PID is used extensively in fields such as servo motor control, robotics, temperature control and power electronics. It has a long history of development and very mature tuning rules. Overall, the PID is an important tool for the embedded real time digital controls designer.

They are usually implemented either in hardware using analog components or in software using computer-based systems. Recently, the emergence of field programmable gate arrays and hardware description languages now allows for added dimensions of digital PID controllers' parallelism, Programmable bit widths and absolute determinism. Building PID controllers on Field Programmable Gate Arrays (FPGAs) improves speed, accuracy, power-efficient, compactness and cost effectiveness.

With the growing complexity of motor and motion control applications, it becomes apparent that a Field Programmable Gate Array (FPGA) offers significant advantage over the off shelf Application Specific Standard Product (ASSP) solutions in the areas of performance, flexibility and inventory control.

With an FPGA, calculations that would normally consume large amounts of CPU time when implemented in software may be hardware accelerated. Using hardware acceleration allows for more functionality within the system software. Furthermore, by varying the hardware configuration during operation time without changing the number of gates and the power demand, controllers based on such hardware devices can adapt to different operating conditions. Such a feature is particularly useful [2]. Custom motor drive interfaces such as Pulse Width Modulation (PWM) can be developed easily, quickly and at low cost. Additionally, because of full configurability, the same FPGA can be used in various product ranges, reducing the need to maintain inventory for multiple devices [3].

The Spartan3 family of Field-Programmable Gate Arrays is specifically designed to meet the needs of high volume, cost-sensitive consumer electronic applications. The eight-member family offers densities ranging from 50,000 to five million system gates. Because of their exceptionally low cost, Spartan3 FPGAs are ideally suited to a wide range of consumer electronics applications, including broadband access, home networking, display/projection and digital television equipment.

Modern FPGAs and their distinguishable capabilities have been advertised extensively by FPGA vendors [4]. Moreover, some refereed articles addressed the advantages of utilizing these powerful chips [5-6]. In the past two years, Spartan II and III FPGA families from Xilinx have been successfully utilized in a variety of applications, which include inverters [7-8], communications [9-10], embedded processors [11], and image processing [12]. The implementation of PID controllers using microprocessors and Digital Signal Processor (DSP) chips is old and well known [13-14], whereas very little work can be found in the literature on how to implement PID controllers using FPGAs. The scheme proposed by Y. F. Chan, M. Moallem and W. Wang [15] is based on a distributed arithmetic algorithm where a Look-Up-table (LUT) mechanism inside the FPGA is utilized.

A PWM generator is introduced in [16]. However, only simulation results are presented and the proposed algorithm results in greater consumption of FPGA resources however, despite its complexity, the algorithm in [16] is superior in terms of harmonic content and is more suited to inverter

applications. The contributions of the authors in [17-20] are considered complementary to the present work as they provide tools for building the current application.

The software developed provides the user interface through on board peripherals like Pushbuttons, Toggle switches, Light Emitting Diodes (LEDs) and Seven Segment Displays, so that the user can change the set speed of the motor as well view the data display on Seven Segment Display and also reset the entire system.

The organization of this paper is given as follows: In section 2, an overview of the functional modules of a FPGA based PID controller for DC motor speed control system are explained. In section 3, State flow diagrams of the present design are presented. In section 4, the implementation results of the system are discussed. Conclusions are discussed in section 5.

2. Overview of Functional Modules

The target FPGA device used in this research is Spartan3 family XC3S400 manufactured by Xilinx. Design development and debugging is carried on a low-cost, full-featured kit provided by Advanced Electronic Systems (ALS). This board provides all the tools required to quickly beginning designing and verifying Spartan3 platform designs. Designs are based on 10 MHz clock.

Fig. 1 shows the Hierarchical Diagram of FPGA Based PID Controller Implementation for DC motor speed control system. Fig. 2 shows the PID Controller Top level module with sub modules with internal and external signal flow. The software tools used for building and testing these modules in the present work are Xilinx ISE 9.2i and ModelSim XE III 6.3c.

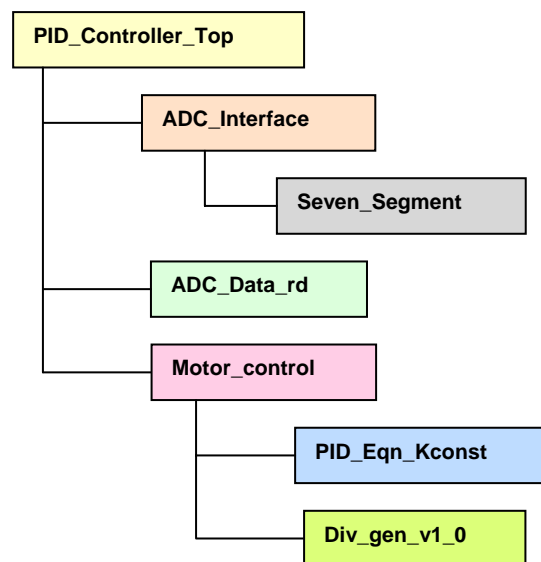


Fig. 1. Hierarchical Diagram for FPGA based PID controller Implementation.

2.1. PID Controller Top Module

The PID Controller Top module is the Main Top level VHDL module in the hierarchy. It instantiates the sub modules ADC_interface, ADC_Data_Read and Motor_control modules. It interconnects all the signals and interacts with the external world.

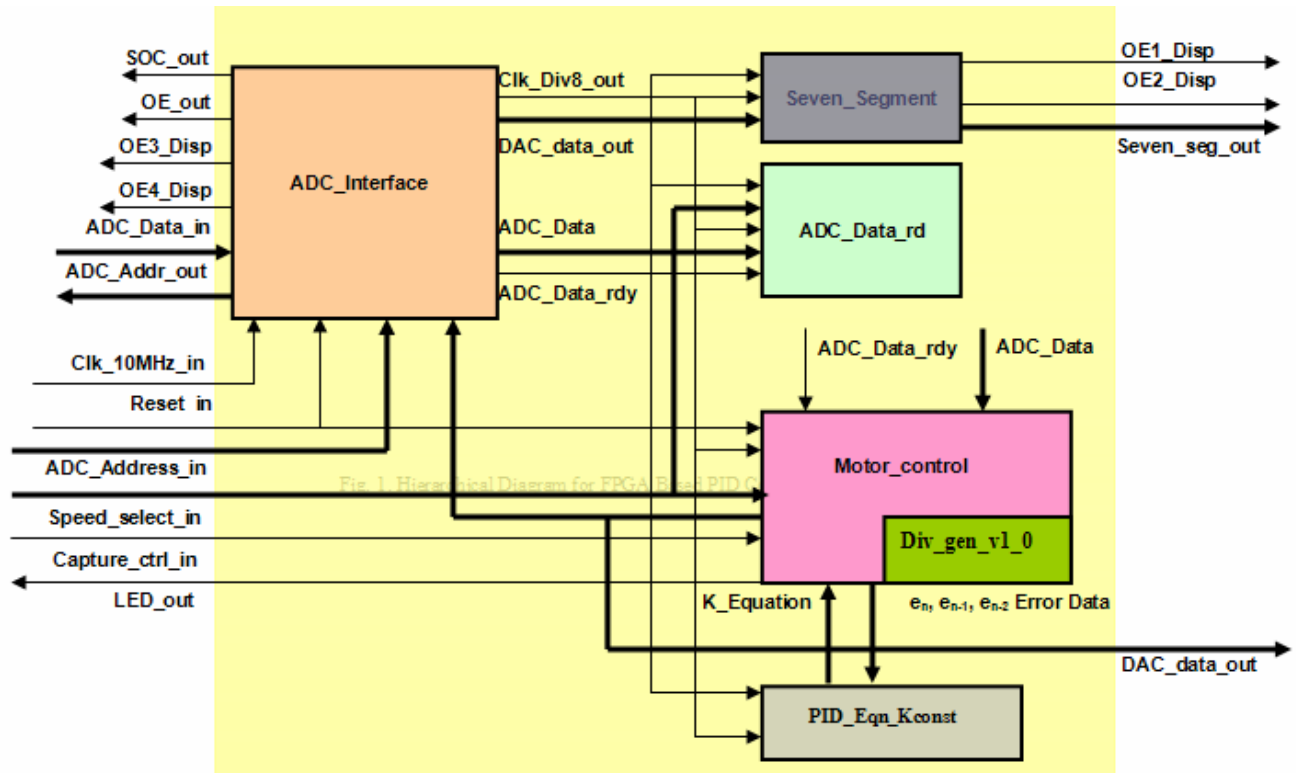


Fig. 2. PID Controller Top module with sub modules.

2.2. ADC Interface Module

It is a front end interface module for ADC. This module has a state machine `ADC_state` that gives out the signals Start Of Conversion (SOC) and Output Enable (OE) for ADC. It also generates ADC channel address based on the three bit on board toggle switch (TS1, TS2, TS3) input. After asserting these signals it waits for End Of Conversion (EOC) signal, which is 8th bit in the data bus.

Once ADC asserts EOC the state machine generates the `ADC_Data_Ready` signal used as enable for the register that latches the valid data from the ADC. Also the same signal will be given to the next module, ADC Data Read module that uses this as a control signal for latching the valid data. The Sub module `Seven_Segment` is used for seven segments Display that will display the data going to Digital to Analog Converter (DAC) hardware module, which is the actual speed, calculated using the PID equation.

2.3. ADC Data Read Module

The ADC data read module takes the ADC data from ADC interface module based on the control signal `ADC_data_rdy_in`. It has a state machine `ADC_RD_State` which checks for `ADC_data_capture` switch, a toggle switch input connected to the switch input `capture_ctrl_in` (TS16) in top module. Once this switch is asserted it proceeds to next state and checks for the `ADC_Data_ready` input signal from ADC interface module. When the `ADC_Data_ready` signal is asserted it will wait for 200 cycles in next state and asserts `ADC_AVG_DATA_Rdy` signal, which will register the 200th ADC data. Process waits 200 cycles for ADC data to get stabilized after change in speed of motor. The latched data along with the control signal `ADC_AVG_DATA_Rdy` will be sent out to next module, which is Motor control module.

2.4. Motor Control Module

The Motor control module receives the data from ADC Data Read module, which is latched into the module using ADC_AVG_DATA_Rdy control signal from the ADC Data read module. Once the data is latched into the module it calculates the current speed, which is the ADC data multiplied by 10. The maximum speed for the motor is considered as 2550 rpm which if divided by 10 to get 255 in decimal, equivalent to “11111111” in binary, which is the maximum 8 bit ADC value. This is done to get the approximated current speed.

Once the current speed is calculated, this value is subtracted with the set speed value, which is set using the toggle switches Speed_Set_switch, connected to Speed_select_in, in PID controller top module. This will generate current error e_n . The same e_n will become e_{n-1} and e_{n-2} in next consecutive cycles. The values of e_n , e_{n-1} and e_{n-2} are fed to PID equation calculation module with their polarity, which indicates whether the calculated value is positive or negative.

The PID Equation calculation module will calculate $K_{equation}$ value, which is a part of PID equation,

$$[K_p * (e_n - e_{n-1}) + K_i * e_n + K_d * (e_n - 2 * (e_{n-1}) + e_{n-2})].$$

The final PID equation

$$[V_{n-1} + K_p * (e_n - e_{n-1}) + K_i * e_n + K_d * (e_n - 2 * (e_{n-1}) + e_{n-2})]$$

will be calculated in Motor control module. It has several state machines like Motor_Control_State, PID_Assign_State, SW_Debounce_State and Speed_Lock_State.

In Motor_Control_State machine capture enable switch is monitored which is connected to Captur_ctrl_in switch in the top module. Once this is asserted the controller waits for some delay until valid data for PID equation is calculated. Now, swap the values of errors e_n , e_{n-1} and e_{n-2} and also PID values V_n and V_{n-1} are swapped.

PID_Assign_State machine checks the calculated PID value for negative or greater than 255 the maximum value of ADC. If it is negative then DAC is assigned Zero, else if the value is greater than 255, 255 is assigned. If the value is between 0 and 255 then the actual value for DAC is assigned.

SW_Debounce_State machine wait for some fixed amount of delay to overcome the de-bouncing of the speed select toggle switches.

Speed_Lock_State machine check whether the calculated speed lies with in plus or minus 100 rpm range of set speed, if so, it is approximated to the set speed. This approximation is done, as floating point operation is not considered in calculating the PID equation, which is beyond the scope of this design. Once the calculated speed is ready by PID equation, it is divided by 10 using the divider module to get the equivalent DAC value. This is based on the approximation for rpm, which was done in the beginning while calculating the current speed from ADC data. Once the equivalent binary data is calculated from PID equation it is sent to DAC. This will continue until all the errors become zero and V_n equals V_{n-1} , which forces current speed equal to set speed and hence motor starts running at set speed.

2.5. Coregen Divider Module

This is Xilinx specific coregen module, used in the present design. Instantiated in Motor Control Module to divide the calculated PID value V_n to get the equivalent binary value, which has to be sent to DAC.

2.6. Seven Segment Display Module

This module will generate the output enable for on board seven segment displays and also provide the data to seven segment modules, which is going out to DAC.

2.7. PID Equation Calculation Module

The calculated errors e_n , e_{n-1} and e_{n-2} with their polarities, whether they are positive or negative is fed to this module from motor control module. This module will calculate the part of PID equation,

$$V_n = V_{n-1} + K_p * (e_n - e_{n-1}) + K_i * e_n + K_d * (e_n - 2*(e_{n-1})) + e_{n-2}$$

which is

$$K_p * (e_n - e_{n-1}) + K_i * e_n + K_d * (e_n - 2*(e_{n-1})) + e_{n-2}.$$

The constants K_p , K_i and K_d values are 3, 2 and 1 respectively. They are calculated by trial and error method.

The PID equation is evaluated part by part. First the values for $K_d * (e_n - 2*(e_{n-1}))$, $K_i * e_n$ and $K_p * (e_n - e_{n-1})$ are individually calculated retaining their polarity, which will determine whether the calculated values are positive or negative. Once this is done combined equations,

$$K_d * (e_n - 2*(e_{n-1})) + e_{n-2} \text{ and } K_p * (e_n - e_{n-1}) + K_i * e_n$$

are calculated with their polarities. Once these equations are evaluated, the final K equation is calculated which is,

$$K_p * (e_n - e_{n-1}) + K_i * e_n + K_d * (e_n - 2*(e_{n-1})) + e_{n-2}.$$

This is fed back to Motor control module with K equation polarity that will determine, whether the calculated value of K equation is positive or negative.

In motor control module the final PID equation,

$$V_n = V_{n-1} + K_p * (e_n - e_{n-1}) + K_i * e_n + K_d * (e_n - 2*(e_{n-1})) + e_{n-2}$$

is calculated.

Here the polarities of current errors and current PID value are passed to polarities of previous PID and previous errors to hold their polarity for further calculations. For example, if the error e_n and its polarity calculated are negative, then in the next cycle the e_n value is assigned to e_{n-1} and the polarity of e_n becomes e_{n-1} polarity.

3. State Flow Diagrams

The state flow diagrams are so drawn that, they are self explanatory and gives the complete idea of software development for FPGA based PID controller for DC motor speed control system. Fig. 3 shows State flow diagram for ADC_State, state machine in ADC Interface module. Fig. 4 shows State flow diagram for ADC_RD_State, state machine in ADC Data read module and Fig. 5 shows State flow diagram for Motor_Control_State, state machine, Fig. 6 shows State flow diagram for PID_Assign_State, state machine, Fig. 7 shows State flow diagram for SW_Debounce State, state machine, Fig. 8 shows State flow diagram for Speed_lock_state, state machine in Motor control module.

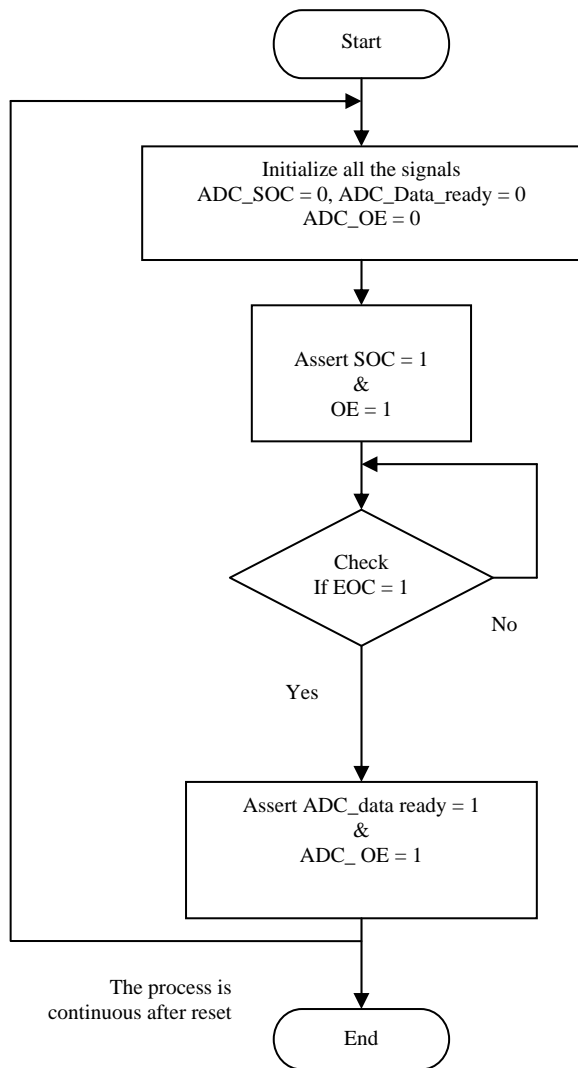


Fig. 3. State flow diagram for ADC_State, state machine.

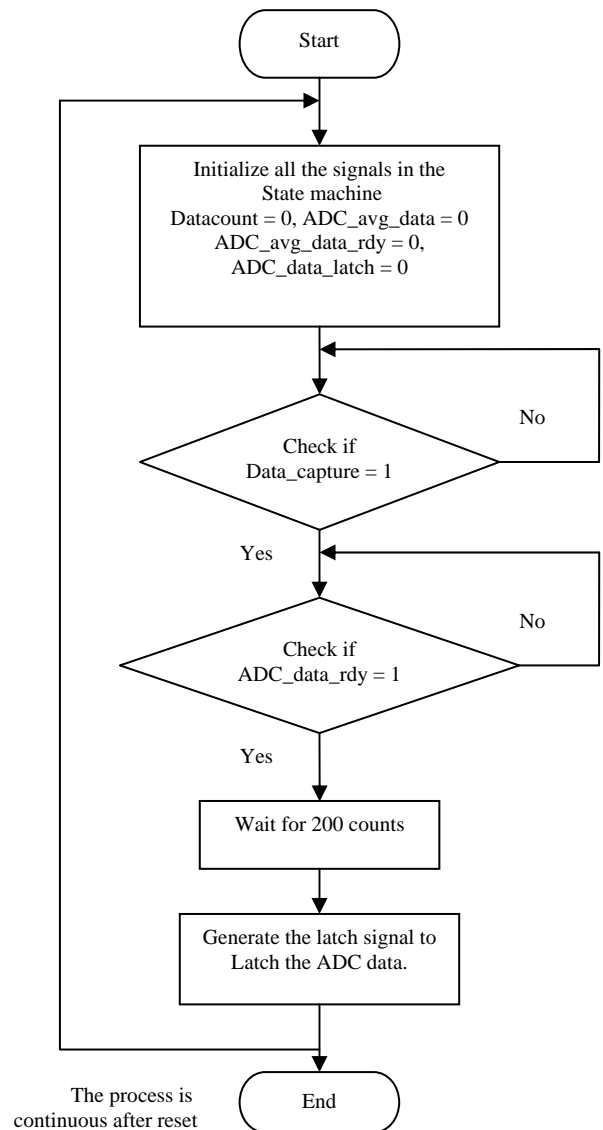


Fig. 4. State flow diagram for ADC_RD_State, state machine.

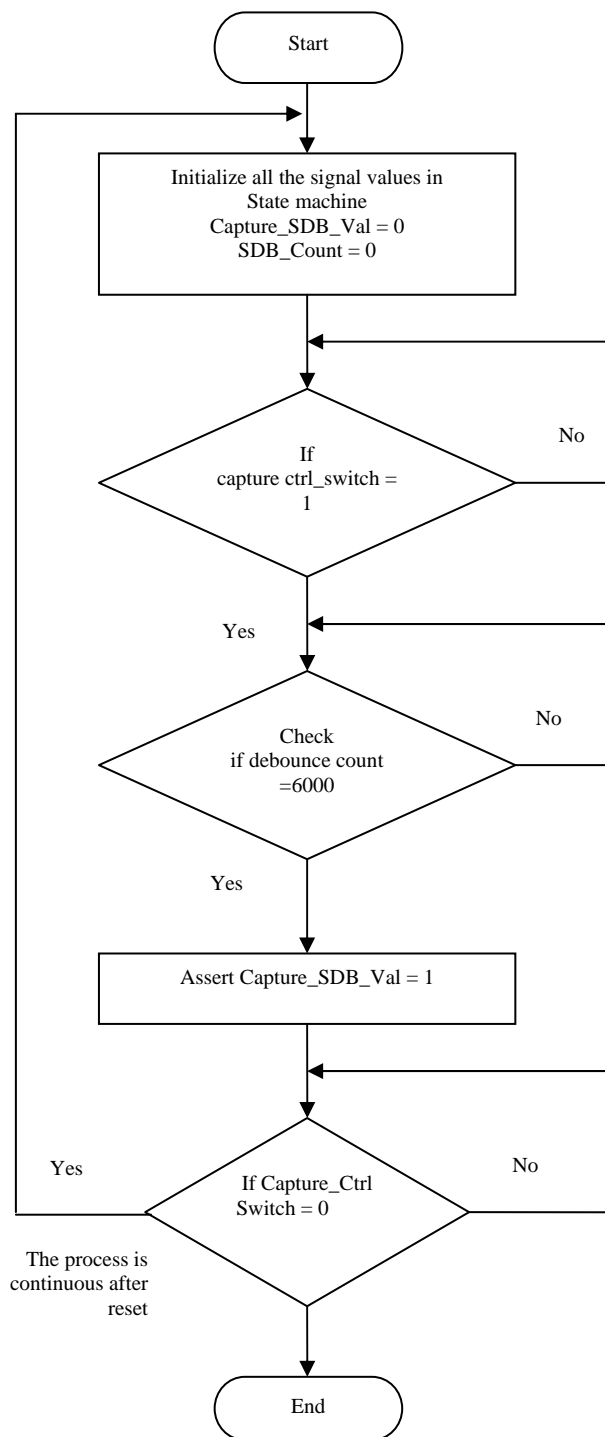


Fig. 5. State flow diagram for Motor_Control_State, state machine.

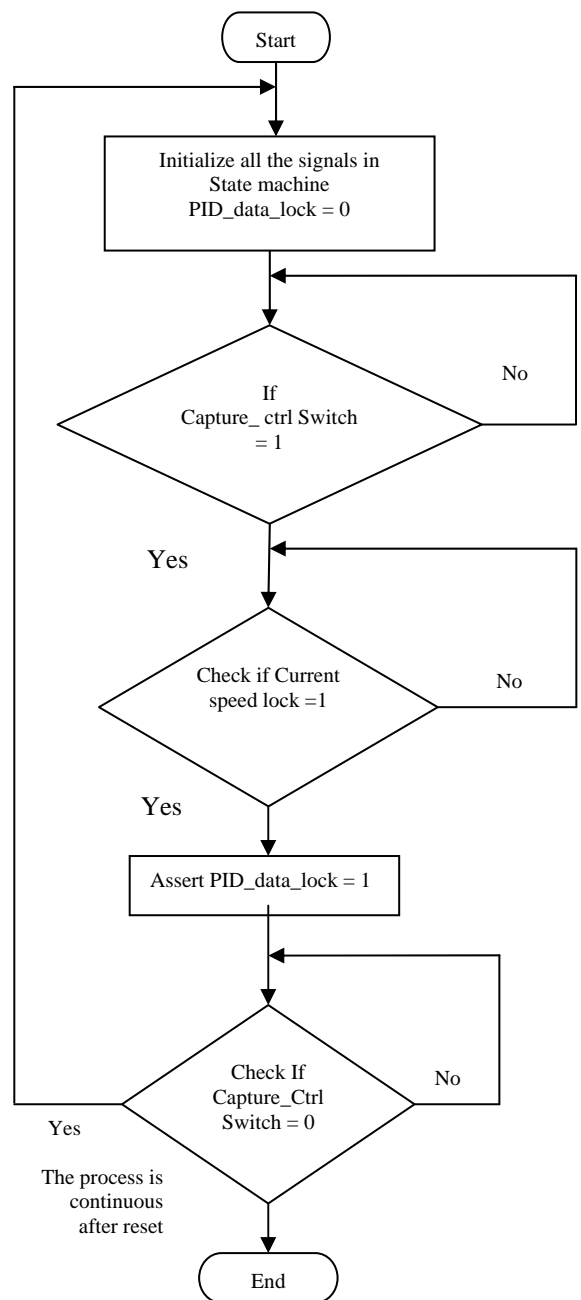


Fig. 6. State flow diagram for PID_Assign_State, state machine.

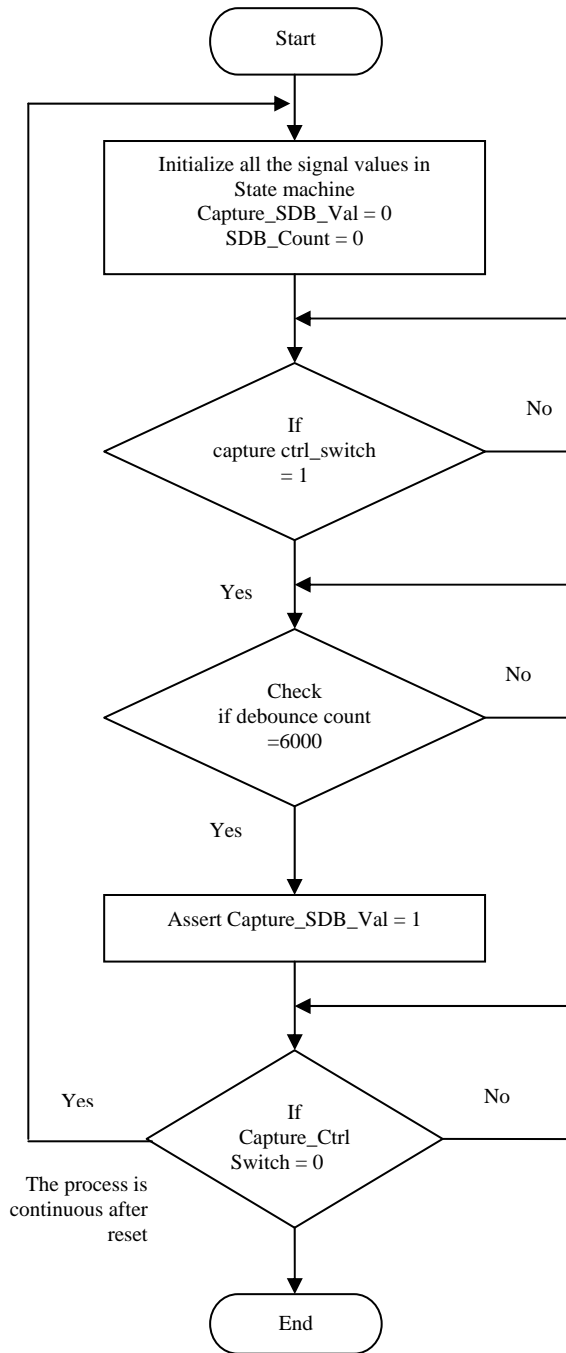


Fig. 7. State flow diagram for SW_Debounce State, state machine

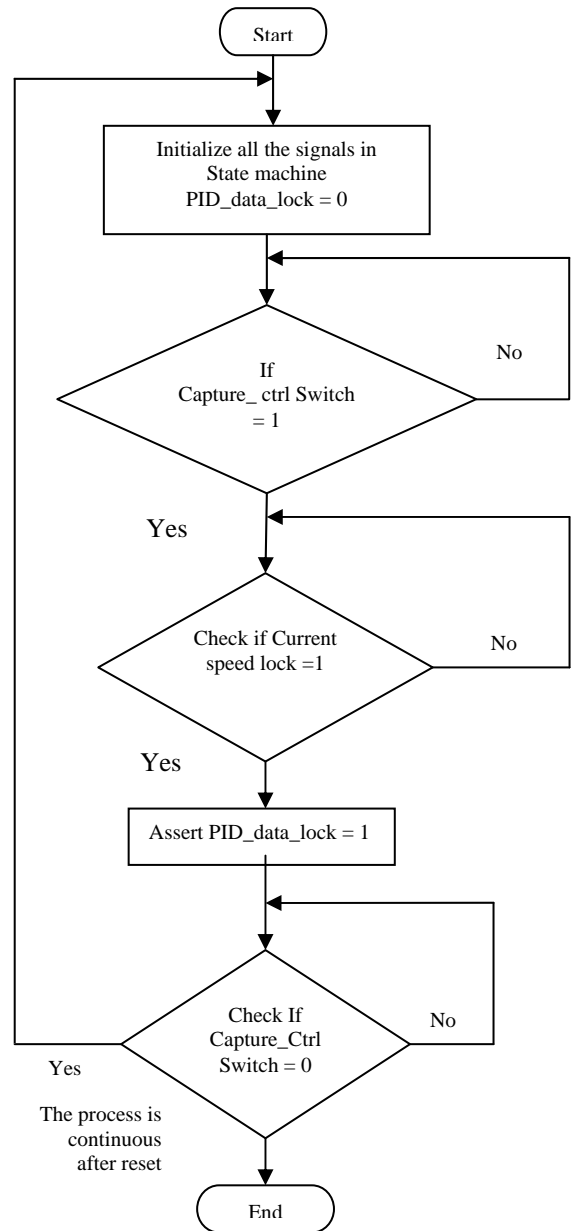


Fig. 8. State flow diagram for Speed_lock_state, state machine

4. Results

4.1. Simulation Results

Logic simulation in any FPGA design environment plays a very vital role in verifying the functionality of the designs. Simulation is a powerful way to test the system on a computer, before it is turned into hardware. Simulators let designer to check the values of signals inside the system.

In the present study, for functional verification, before verifying the performance of proposed controller design on FPGA, the complete design is simulated using Modelsim Simulation tool (Xilinx version ModelSim XE III 6.3c), which has pre-compiled libraries for all Xilinx FPGAs.

A test bench is written where, the set speed can be changed for the motor. In the test bench, the Top module of the design PID_controller_top is instantiated. The inputs like Clock, Reset, Switch data and ADC data are defined and the output is observed in the simulation window.

As many sub modules are instantiated in Top module and as this is a hierarchical design, internal sub module signals are also observed in the waveform window of the simulator. Once all the signals are taken into the waveform window, the simulation is run for 1000 microsecond and the required changes in the signals are observed in the waveform window. It is observed that the motor speed gradually changes to the set speed and locks to the set speed. The simulation results show the improved quality of the PID controller.

Fig. 9 shows the simulation results for the set speed of 1400 rpm. It is seen that after certain transitions, when the errors e_n , e_{n-1} and e_{n-2} become zero, the current speed will become 1400 rpm which is equal to set speed. The data going to the DAC, PID_data_out is equal to 140, which is the current speed, the transitions in the state machines that are assigning current value to e_n , e_{n-1} , e_{n-2} and V_{n-1} are observed in the waveform window.

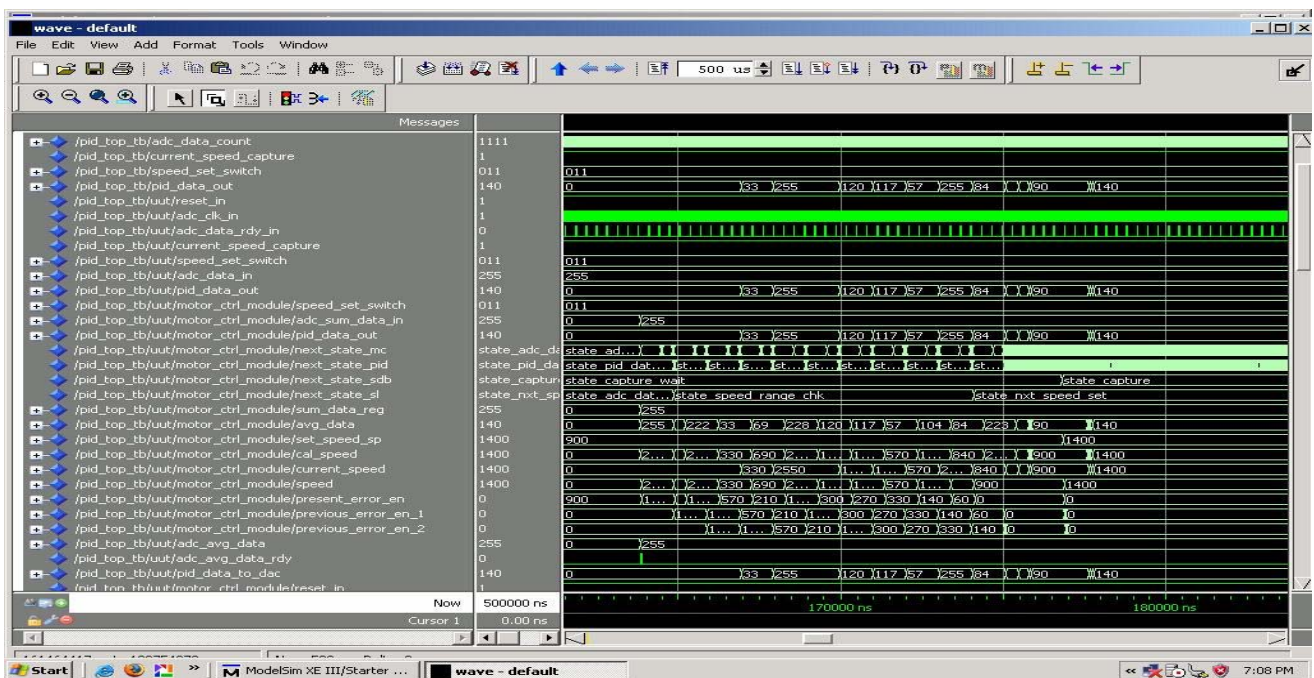


Fig. 9. Simulation waveforms for set speed 1400 rpm.

Finally, from the waveforms it is observed that, when the optimal values for K_p , K_i and K_d are used to calculate the current speed, the current speed will equal the set speed when all the errors e_n , e_{n-1} and e_{n-2} become zero, hence V_n equals V_{n-1} and the motor starts running at the set speed.

Table 1 shows the Design Summary, Xilinx tool device utilization summary and reports the percentage of available resources that have been used for the current FPGA design. The performance summary summarizes the timing requirement and also the proper routing of the signals.

Table 1. Design Summary of FPGA based PID controller for DC motor Speed control system.

ADCINTERFACE Project Status					
Project File:	ADCINTERFACE.isc	Current State:	Programming File Generated		
Module Name:	PID_controller_top	Errors:	No Errors		
Target Device:	xc3s400-5pq208	Warnings:	3 Warnings		
Product Version:	ISE 9.2i	Updated:	Wed Aug 20 13:47:36 2008		
ADCINTERFACE Partition Summary					
No partition information was found.					
Device Utilization Summary					
Logic Utilization	Used	Available	Utilization	Note(s)	
Number of Slice Flip Flops	2,638	7,168	36 %		
Number of 4 input LUTs	2,358	7,168	32 %		
Logic Distribution					
Number of occupied Slices	1,916	3,584	53 %		
Number of Slices containing only related logic	1,916	1,916	100 %		
Number of Slices containing unrelated logic	0	1,916	0 %		
Total Number of 4 input LUTs	2,358	7,168	32 %		
Number of bonded IOBs	43	141	30 %		
IOB Flip Flops	16				
Number of MULT18X18s	3	16	18 %		
Number of GCLKs	2	8	25 %		
Total equivalent gate count for design	56,447				
Additional JTAG gate count for IOBs	2,064				
Performance Summary					
Final Timing Score:	0	Pinout Data:	Pinout Report		
Routing Results:	All Signals Completely Routed	Clock Data:	Clock Report		
Timing Constraints:	All Constraints Met				
Detailed Reports					
Report Name	Status	Generated	Errors	Warnings	Infos
Synthesis Report	Current	Sun Aug 17 12:30:06 2008	0	0	0
Translation Report	Current	Sun Aug 17 12:30:48 2008	0	0	0
Map Report	Current	Sun Aug 17 12:31:18 2008	0	2 Warnings	3 Infos
Place and Route Report	Current	Sun Aug 17 12:33:47 2008	0	1 Warning	3 Infos
Static Timing Report	Current	Sun Aug 17 12:34:08 2008	0	0	3 Infos
Bitgen Report	Current	Sun Aug 17 12:34:53 2008	0	0	0

4.2. Hardware Test Results

The experimental studies are carried out to evaluate the performance of the controller. Configuration is the Process by which the bit streams of a design, as generated by the development software are loaded

into the internal configuration memory of the FPGA. To verify the performance of the controller design on Hardware, the VHDL code (Bit file) is downloaded into the Target FPGA device (Spartan 3 family XC3S400) and the complete system is reset. The set speed is assigned to switches according to the requirement and the capture control switch is enabled. Once this is done the ADC data will be read and PID equation implemented will calculate the equivalent PID value and it is fed back to the motor through DAC and once the current speed equals the set speed, the motor starts running at the set speed. Again to change the set speed, the above procedure is repeated by changing the toggle switch position.

As the set speed is varied, the ADC voltage also varies, the measured ADC values and the equivalent Hex values for different set speeds are tabulated. It is observed that the current speed, which is displayed, on the 'on board' seven segment display equals the set speed value. Also the change in the motor speed for different switch combinations can be observed accordingly. Table 2 shows the results of the DC motor speed control system for various set speeds. Fig. 10 shows the Photograph of the experimental setup and working model of FPGA based DC motor speed control system.

Table 2. Results of DC motor speed control system for various set speeds.

Sl. No	Toggle Switch position	Set Speed (rpm)	Equivalent HEX value	Measured ADC voltage (V)
1.	000	2500	FA	4.5
2.	001	1200	78	2.4
3.	010	400	28	0.64
4.	011	1400	8C	2.8
5.	100	2000	C8	3.63
6.	101	600	3C	1.15
7.	110	1100	6E	2.04
8.	111	900	5A	1.8



Fig. 10. Photograph of the experimental setup and working model of FPGA based DC motor speed control system.

5. Conclusions

A digital PID controller is successfully implemented using the FPGA and its performance is verified and tested on a DC motor speed control system for real-time control. The test results showed that with the addition of PID controller added, the steady-state error is eliminated and the desired output speed is obtained. The implementation of controller has reduced the total hardware complexity and cost.

According to the experiment done it is observed that, in the simulation, when the set speed is changed, the motor speed locks to the set speed, when the current error e_n , previous error e_{n-1} and previous to the previous error e_{n-2} becomes zero.

In brief, the role of FPGA, in measurement and control point of view, is to acquire the data from sensor through analog to digital converter, do the processing on the acquired data and then generate control signals to the actuator, which in turn controls the parameter being measured. FPGAs ensure ease of design, lower development costs, more product revenue, and the opportunity to speed products to market. Building PID controllers on FPGAs improves speed, accuracy, power-efficient, compactness and cost effectiveness over other digital implementation techniques.

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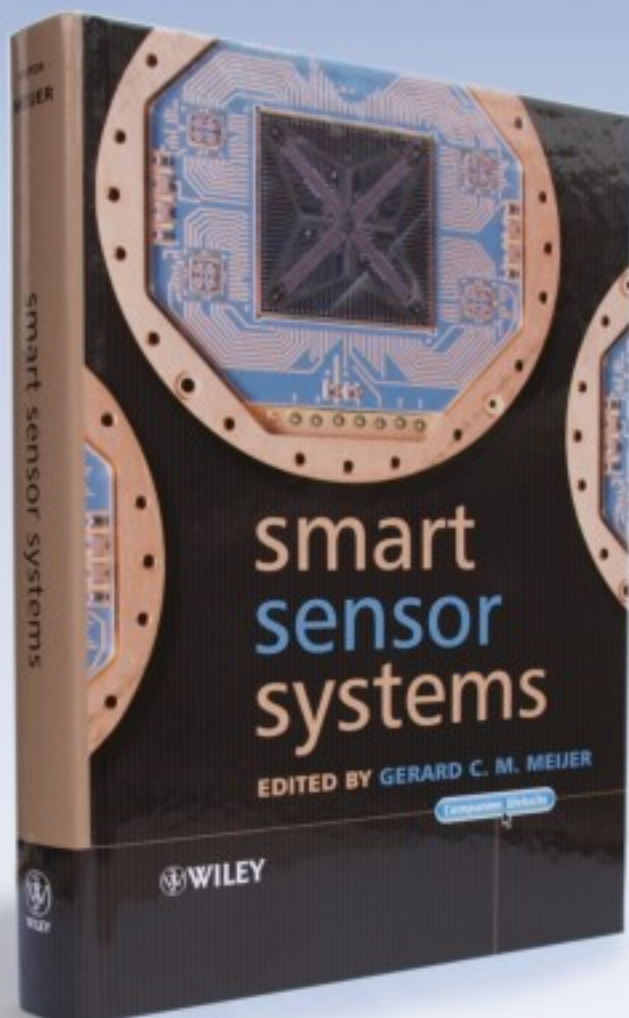
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