Design and Implementation of a Two Stage Controller for Ball and Beam System Using FPGA

Ivan A. Hashim
University of Technology, Electrical Engineering Department
Baghdad, Iraq.
k300o@yahoo.com

Ekhlas H. Karam
University of Al Mustansyria, Computer Engineering Department
Baghdad, Iraq.
ek_karam@yahoo.com

Noor S. Abdul-Jaleel
University of Al Mustansyria, Electrical Engineering Department
Baghdad, Iraq.
mail_ns1@yahoo.com

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Abstract- *The ball and beam is, in fact, a standout amongst the essentially vital models, which are generally utilized for educating the control system because its simplicity to be built, modeled, and controlled. This system involve a ball roll on a beam and since the angle of the beam manipulate by servo motor, so the purposes of this paper is to design two stages controller to stabilize the ball position along the beam by varying the angle of beam. The First controller stage is Proportional-Integral- Derivative (PID) for servo motor. The second stage of the controller is Proportional-Derivative (PD) to control the ball and beam plant. The Matlab simulation results illustrate the efficiency of this controller. Furthermore, this paper presents the complete hardware Field Programmable Gate Arrays (FPGA) design with real time implementation for the suggested controller. This controller utilized 1% of occupied slices when implement on Spartan-3A DSP 3400A Xilinx kit with* 70.265 ns *minimum time required to complete the controller function. The experimental tests shows that the suggested two stages controller satisfy the functional requirements results.*

Keywords- *ball and beam system; discrete PID; FPGA design; PD controller; PID controller; servo motor.*

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1. Introduction

The ball and beam system is one of the most important models laboratories for control systems engineering teaching. This system is often used since it is simple to understand, open loop unstable and hence the different control approaches (classical, modern and adaptive) can be used to design a suitable controller of it [1]. The main work of ball and beam control is so difficult because it must maintain the place of ball on the beam by varying the angle of beam, while the ball still moving with the acceleration, which is proportional to the slope of the beam, and not stay in one position. The system in case of open loop becomes unstable, when the place of ball (the output system) increasing with constant angle of beam (the input system) without limited. Therefore, feedback system should apply to make the system more stabilize and maintain the ball in the performance place [1]. One of the most widely used controllers for ball and beam system and other control industries is the Proportional Integral and Derivative (PID) controller because it's simple to design, robustness and easy to use [2]. However, the application of digital PID controller involves the use of microprocessors or microcontrollers. Whilst the processor brings, decipher the code and implement the program directive, the memory carry the application program. This method has disadvantages in the speed of processes when these processes depend on software, which requires many instrument cycles to implement. Because the operations on FPGA are suitable hardware, the FPGA-based digital PID controller is suggested which achieved best speed performance [3].

In general, the Field Programmable Gate Arrays (FPGA) is consider as one type of programmable logic devices PLDs which is based on an integrated circuit that can be formatted by the user in order to perform digital logic functions of different involvements such in [4, 5]. In addition, it can be very efficiently used for control systems like the processes that require highly loop of time cycle. FPGA applications involve industrial motor drivers, real time systems, digital signal processing, computer hardware simulation and a mounting space of other areas. The basic advantage of FPGA compare with DSP and other microprocessors is the unrestrained of programming parallelism. The different parts of

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FPGA enable to shaped to implement independent functions with each other, this execution is not connected to clock rate as in DSPs [6]. Because of that, FPGAs can score over public purpose computing chips in implementation of the digital control systems. FPGAs considered as one of the fastest rising parts of the digital integrated circuit market in the latest years, because it can be used to merge large amounts of logic in a single IC [7]. A few surveys were made for performance PID controllers on FPGAs, though; many works have been suggested to processed PID controllers. Pourya and Arash [3] suggest FPGA-based digital PID controller depends on floating point math for calculations, Gupta and Khare [7] proposed a procedure to design the PID controller in simulink but without done in practical works. Mohammed et al. [8] design FPGA that reduce in the cost by minimizes the hardware. A fixed-point of digital PID controller was designed in Xu and Shuang [9] that showed a high accuracy, wide dynamic range and fast response of speed could be obtained. Sonoli and Nagabhushan [10] controlled the DC motor by using FPGA, which is based on PID controller. In [11] designed an encoder and digital PID controller by using simulink model of Xilink system library. In [12] the researches designed the PID controller to achieve a balance between the speeds and the resources of FPGA. Patel & Singh [13] suggested to design FPGA depended on PID controller based on “Spartan3e XC3S100E” FPGA. [14] Presents a new technique for controlling the motion of a permanent magnet of the DC motor by implementation of FPGA which is based on PID controller. In other word, and since the two stage (cascade) controller is one of the most efficient approaches that is used to control the ball and beam system and it present in many references like [15-17], so in this paper, a two stages controller (PID with PD) is suggested first to control the servo motor and ball and beam system, then these two stages are designed in real time by using FPGA. This paper is organized as follows: the mathematical model of the ball and beam system is given by section 2, the suggested two stages controller for ball and beam system is describes in section 3, the complete hardware FPGA design is explained by section 4, various Matlab simulation results are illustrate by section 5, the summary for the overall work and conclusions are given in last section of this paper.

2. Mathematical Model for Ball and Beam System

In general, the ball and beam system consists of a long beam mounted on the output shaft of a servo motor and steel ball rolling on the top of this beam as shown in Figure 1. Therefore, the beam will be tilted about the center axis of it by the control signal that generated by the amplifier of the servo motor [1]. A brief description for the dynamic model of the ball and beam system and servo motor are provide in this section, so this section include two parts:

1. Mathematical Model of Ball and Beam system.
2. Mathematical Model of Servo Motor system

I. Mathematical Model of Ball and Beam System

The schematic of the ball and beam system is shown in Figure 2.and the parameters of this system are defined by Table 1.

In general, Lagrangian method or Newton’s second law can be used to drive the dynamic equations of the ball and beam system.

Figure 1: Real ball on a beam system

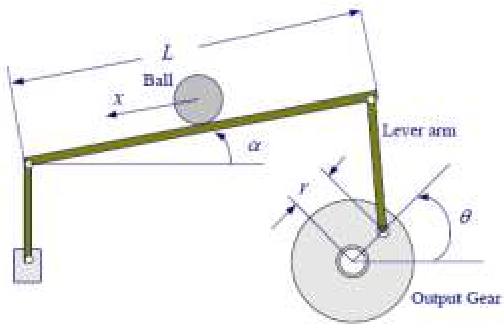


Figure 2: Schematic of the ball and beam system

Table 1: The parameters of ball and beam system

Symbol	Description	Value	Unit
L	Beam length	16.75	cm
R	Lever arm offset	1	in
g	Gravitational acceleration	9.8	m/s^2
J	Ball's moment of inertia	$2/5\ mR^2$	
α	Beam angle coordinate		
θ	Servo gear angle		
m	Mass of ball		

R	Radius of the ball

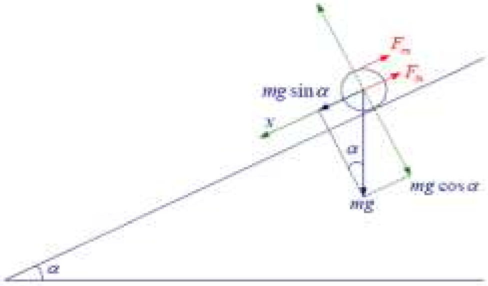


Figure 3: Rolling ball free-body diagram

According to Newton's second law, the relation between the position of the ball x and the beam angle α can be determine from the free-body diagram shown in Figure 3 with neglect the frictional force by the following equation [1, 17]:

$$F_{rx} + F_{tx} = mg\ sin\alpha \qquad (1)$$

Where: F_{tx} is force due to translational motion which equal to:

$$F_{tx} = m\ddot{x} \qquad (2)$$

The $\ddot{x}$ is the acceleration $\frac{d^2 x}{dt^2}$ along x, while F_{rx} is force due to ball rotation given by:

$$F_{rx} = \frac{J}{R^2}\ddot{x} \qquad (3)$$

With $J = \frac{2}{5}\ mR^2$ which is the moment of inertia of the ball, the equation (3) becomes:

$$F_{rx} = \frac{2}{5}\ m\ddot{x} \qquad (4)$$

Substituting equation (2) and equation (4) in equation (1), we get:

$$\frac{2}{5} m\ddot{x} + m\ddot{x} = mg\ sin\alpha$$

or

$$\ddot{x} = \frac{5}{7}\ g\ sin\alpha \qquad (5)$$

Equation (5) was linearized for obtaining the transfer function of the ball and beam controller design. For small angle, the variation of α is small, so it can be assumed that *sin* α= α, hence equation (5) becomes:

$$\ddot{x} = \frac{5}{7}\ g\alpha \qquad (6)$$

With Laplace transform for equation (6), it becomes:

$$\frac{X(s)}{\alpha(s)} = \frac{\left(\frac{5}{7}\right)g}{s^2} \qquad (7)$$

Equating the arc distance traversed by the gear at radius r with the arc distance traversed by the beam of radius L, we have $r\theta = L\alpha$ or:

$$\alpha = \frac{r}{L}\theta \qquad (8)$$

In order to make $\alpha = \theta$, we multiply the angle θ by (L/r), so equation (8) becomes:

$$\alpha = \frac{r}{L}.\frac{L}{r}\theta = \theta \qquad (9)$$

And the transfer function of equation (6) becomes:

$$\frac{X(s)}{\theta(s)} = \frac{7}{s^2} \qquad (10)$$

The time response for the closed loop of this function is critical stable because it have two poles ($s_{1,2} = \mp\sqrt{7}j$) lie on the imaginary axis, therefore in order to make this system more stable, a suitable velocity feedback gain=2 is added, hence equation (10) becomes:

$$\frac{X(s)}{\theta(s)} = \frac{7}{s(s+14)} \qquad (11)$$

The state space for equation (11) is:

$$\begin{bmatrix}\dot{z_1}\\ \dot{z_2}\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & -14\end{bmatrix}\begin{bmatrix}z_1\\ z_2\end{bmatrix} + \begin{bmatrix}0\\ 7\end{bmatrix}u$$

$$x = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}z_1\\ z_2\end{bmatrix} \qquad (12)$$

Where u is the input signal, z_1 and z_2 is the state of ball position and velocity respectively, x is the ball position.

II. Mathematical Model of Servo Motor System

The relationship between the input voltage $V_i(s)$ and the beam angle $\theta(s)$ defined by servo DC motor transfer function, which is given by [20, 21]:

$$\frac{\theta(s)}{V_i(s)} = \frac{a_m}{s(s+b_m)} \qquad (13)$$

Where:

$$a_m = \frac{\mu K_m K_g}{R_a J_{eq}}, \quad b_m = \frac{B_{eq}}{J_{eq}} + \frac{\mu K_m^2 K_g^2}{R_a J_{eq}} \qquad (14)$$

The parameters of equation (14) are defined by Table 2.

$$\mu = \mu_{mr}\ \mu_{gb} = (0.87)\ (0.85) = 0.7395 \qquad (15)$$

Equivalent viscose friction referred to the secondary gear.

$$B_{eq} = K_g^2 B_m + B_L \cong 4 * 10^{-3} Nm/(\frac{rad}{s}) \qquad (16)$$

Load inertia:

$$J_L = J_{120} + 2(J_{72}) + J_{24} = 5.2823 * 10^{-3} Kgm^2 \qquad (17)$$

$$J_{eq} = K_g^2(J_m + J_{tach}) + J_L = (14 * 5)^2(3.78 + 0.70) * 10^{-7} + 5.2823 * 10^{-5} = 0.0023\ Kgm^2 \qquad (18)$$

3. Control Scheme for Ball and Beam System

The block diagram for the suggested controller scheme for the (servo motor+ ball and beam) is shown in Figure 4, this controller consist from two stages controller, one for the improve the performance of the servo motor (inner loop) and the other for controlling the ball and beam (outer loop) system, the next subsection explain the controller design for these two stages.

Table 2: The parameters of the servo motor model

Symbol	Description	Value	Unit
R_a	Armature resistance	2.6	Ω
K_m	Motor voltage constant	0.00767	V-s/rad
K_τ	Motor torque constant	0.0767	N-m/A
J_m	Armature inertia	10^{-7}*3.87	Kg m^2
J_{tach}	Tachometer inertia	10^{-7}*0.7	Kg m^2
K_g	High gear ratio	(5)*(14)	
μ_{mr}	Motor efficiency due to rotational loss	0.87	
μ_{gb}	Gearbox efficiency	0.85	
J_{120}	Gear inertia	4.1835*10^{-5}	Kg m^2
J_{72}	Gear inertia	5.4435*10^{-6}	Kg m^2
J_{24}	Gear inertia	1.0081*10^{-7}	Kg m^2

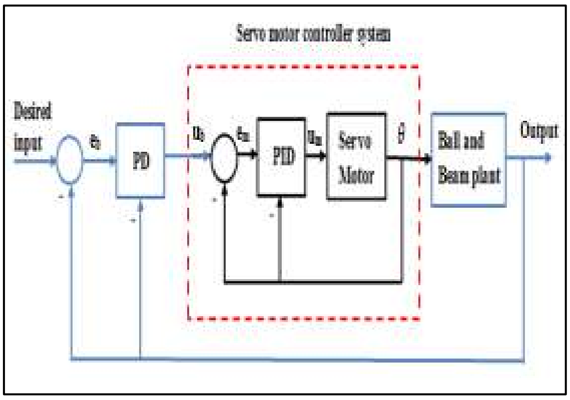


Figure 4: The block diagram for complete controller for ball and beam system

I. PID Controller Design for Servo Motor

The output equation of the PID (first stage) controller for inner loop of the servo motor in s-domain is given by:

$$U_m(s) = (K_{p1} + \frac{K_i}{s})E_m(s) - K_{d1}s\theta(s) \qquad (19)$$

The time domain for this equation is:

$$u_m(t) = K_{p1}\, e_m(t) + K_i \int_0^t e_m(t) - K_{d1}\frac{d\theta(t)}{dt} \qquad (20)$$

Where K_{p1} is proportional gain, K_i is integral gain, K_{d1} is derivative gain, $e_m(t) = \theta_i(t) - \theta(t)$ is the angle error signal, $\theta_i(t)$ is the reference input of servo motor, and $\theta(t)$ is the actual motor position. Many tuning methods can be used to determine the parameters of the PID controller such in references [22-25]. In this paper, the parameters of (K_{p1}=15, K_i= 0.001, and K_{d1}= 1.8) are determine by Launching PID tuner method that provide by Matlab simulink with modification.

II. Controller Design for Ball and Beam System

The outer loop (second stage) controller for ball and beam system consists from PD controller, so

ball controller output signal $U_b(s)$ for this system is:

$$U_b(s) = K_{p2}E_b(s) - K_{d2}sX(s) \qquad (21)$$

Where: K_{p2} is proportional gain, K_{d2} is derivative gain, $E_b(s)$ is the ball error signal ($E_b(s) = X_d(s)$-X(s)), $X_d(s)$ is the desired ball position, $X(s)$ is ball position. The time domain for equation (21) is:

$$u_b(t) = K_{p2}e_b(t) - K_{d2}\frac{dx(t)}{dt} \qquad (22)$$

The parameters of (K_{p2}=14, K_{d2}=0.5) are determine by the manual tuning method, this achieved by changing the PD parameters according to ball response until the desired system response is obtained.

4. FPGA Implementation of the Control Scheme

The Block set of the Xilinx System Generator (XSG) libraries are used to handle the function of the suggested two stage (PID+PD) controller in order to implement this controller using FPGA. The hardware device that used to implement the suggested two stages controller is Spartan-3A DSP XA3SD3400A FPGA Kit. According to characteristics of used device, there are many hardware limitations when implement desired PID and PD by FPGA. Firstly, the number of bits specified for the inputs and outputs of the suggested controller should be not exceed the hardware device bounded pins, at same time these bits should be large enough to represent the smallest change in input signal. In this design, a fixed-point sign number of 16 bits with 8 bits binary point (Fix_16_8) are employed to represent the input signal, while the output signal is specified as (Fix_70_32) in order to produce the best resolution. Hence, the resolution of the output signal is 5.421×10^{-20} which produces perfect accuracy. Therefore, the input/output pins of the suggested PID and PD controllers are 118 pins that easily handled by the selected hardware platform which has 372 bonded input-output pins. Secondly, the design of the integral and derivative of the PID in continues form based on FPGA is very difficult. Therefore, finding the discrete form of equations (20 and 22) is very necessary to solve this issue. Hence, the following equations will be used in designing the suggested (PID+PD) controller based on FPGA:

$$I(k) = \int e(t) = I(k-1) + \left[\frac{e(k)+e(k-1)}{2} * T_{S1} \right] \quad (23)$$

$$d(k) = \frac{de(t)}{dt} = \frac{e(k)-e(k-1)}{T_{s2}} \quad (24)$$

Where: $I(k)$ is discrete time integral by trapezoidal method, $d(k)$ is discrete time derivative, T_{si} is sampling time. Finally, the division operation needed to perform equations (20 and 22) is one of the hardware limitations, because the division process accommodates a large portion of a hardware device. In order to solve this problem the arithmetic shift right is used to perform division by 2 and the multiplication by $1/T_{s2}$ is used instead of the division by T_s. The source file of the blocks used to build the proposed PID and PD controller are export from Xilinx ISE 14.6 to the Matlab via Xilinx System Generator. Figure (5) shows the FPGA design of the suggested two stages controller. Where, A and B represent the system input signal and system output signal, while C represent the actual motor position (θ_o). These signals are converted from double type, which used by Matlab to (Fix_16_8) data type that compatible with FPGA blocks by using 'Gateway In'. Moreover, the 'Gateway In' block is used to convert the data type of controller output from (Fix_70_32) to double. The System Generator is used in order to simulate and implement the proposed system by Matlab/Simulink associative with ISE 14.6.

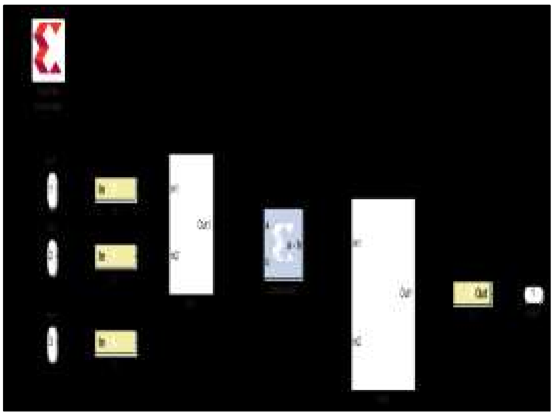


Figure 5: FPGA design of the suggested two stages controller

The FPGA design of the PD and PID controllers are illustrated in Figure 6 and Figure 7 respectively. The output data length of all Xilinx blocks used in this design is optimized to smaller possible number of bits in order to minimize the slices number of Xilinx device when the proposed PD and PID controller are hardware implemented. For the same reason the fixed number length that represents the constant value is reduce to minimum bits that reflect the acceptable resolution. Furthermore, the latency of all multiplier block is minimized to synchronize the Matlab environments with the hardware platform. After the PD and PID controllers are implemented by FPGA design flow successfully, a bit stream source file of the suggested controller is generated and prepared to export to the Xilinx device. The objective of downloading this file is to configure the Xilinx Spartan-3A DSP XA3SD3400A kit corresponding to the suggested controller. Different packages are utilized to download bit stream into the hardware platform; one of them is Matlab, which uses XSG hardware co-simulator to configure the hardware platform and integrate the desired controller operating in FPGA instantly into a Matlab simulation. Therefore, utilizing the HW Co-Simulation is highly important in this design because it is significant to check the Xilinx device by applying the system input signals to the Spartan-3A DSP XA3SD3400A kit with bit stream and find the results. An Ethernet cable is used to interface the proposed controller with Spartan-3A DSP XA3SD3400A kit. Figure 8 shows the HW Co-simulation of the suggested two stages controller after the XSG compiled it. Table (3) shows the device utilization summary of the designed PID and PD controller when the system is implemented using Spartan-3A DSP XA3SD3400A FPGA Kit as a hardware platform. As demonstrate in this table the desired controller takes 1% of the device slices. Moreover, according to timing report description, the allowed maximum frequency for two stages controller is 14.232 MHz; hence, the suggested controller needs approximately 70.265 ns to complete the controller function.

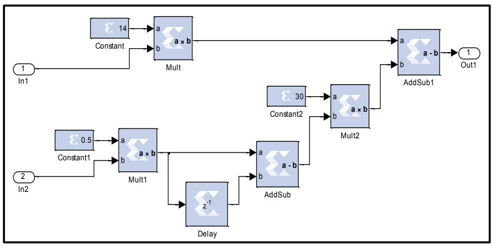


Figure 6: FPGA design of the suggested PD controller

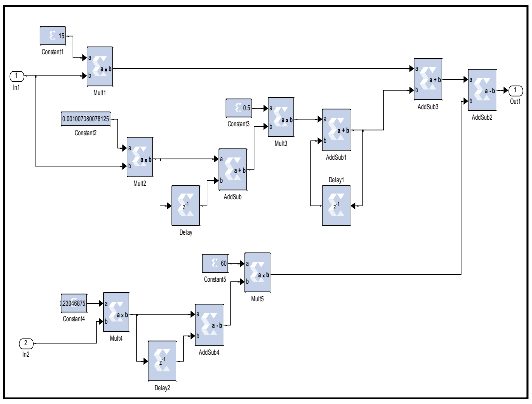


Figure 7: FPGA design of the suggested PID controller

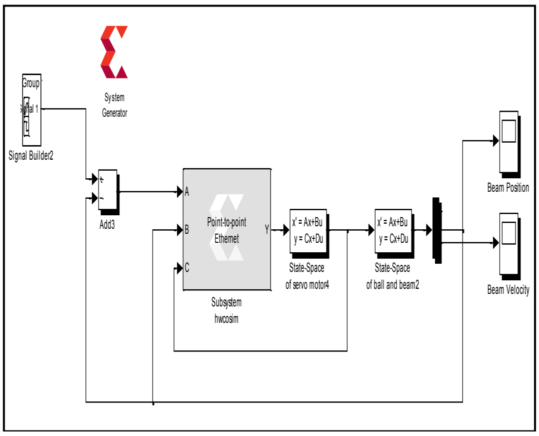


Figure 8: HW Co-simulation of the proposed PD and PID controller

Table 3: Device utilization summary of the designed PID and PD controller

Device Utilization Summary				
Logic Utilization	**Used**	**Available**	**Utilization**	**Note(s)**
Number of Slice Flip Flops	203	47,744	1%	
Number of 4 input LUTs	502	47,744	1%	
Number of occupied Slices	331	23,872	1%	
Number of Slices containing only related logic	331	331	100%	
Number of Slices containing unrelated logic	0	331	0%	
Total Number of 4 input LUTs	518	47,744	1%	
Number used as logic	502			
Number used as a route-thru	16			
Number of bonded IOBs	118	469	25%	
Number of BUFGMUXs	1	24	4%	
Number of DSP48As	21	126	16%	
Average Fanout of Non-Clock Nets	1.23			

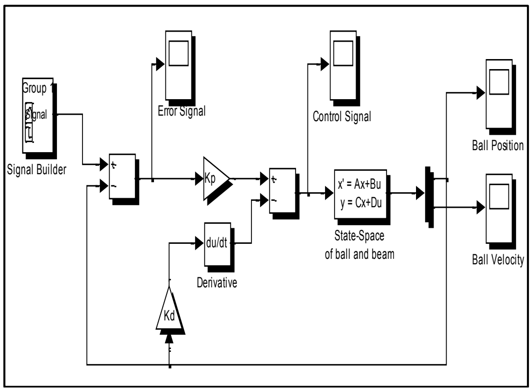
Figure 9: Hardware connection Spartan-3A DSP 3400A and hosting computer

5. Results and Discussion

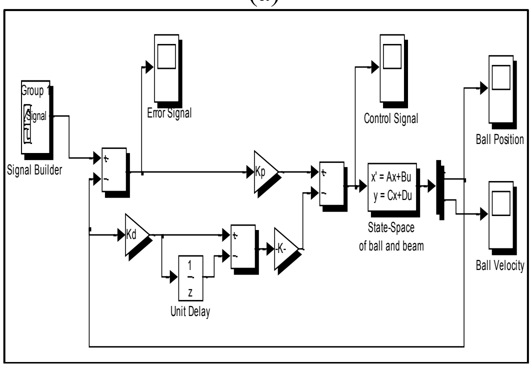
The suggested controller design is presented with Matlab and FPGA system for the ball and beam system. The performance efficiency of the suggested controller is measured and analyzed to study the response of ball and beam system by the following different simulation cases:

I. Simulation Results without Servo Dynamic

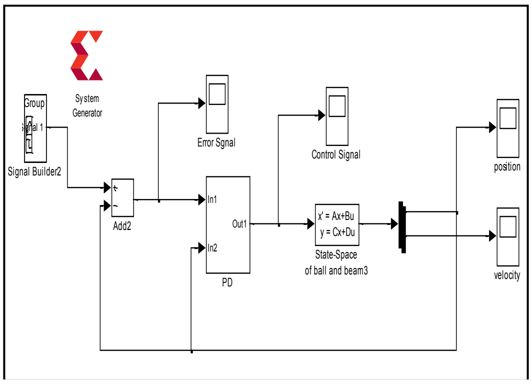
The Matlab Simulink diagram for outer loop (ball and beam) with neglect the servo dynamic model for continuous, discrete, FPGA connection are shown in Figure 10, the simulation results for beam position, beam velocity, control signal, and error signal of these diagrams are shown in Figure 11.



(a)

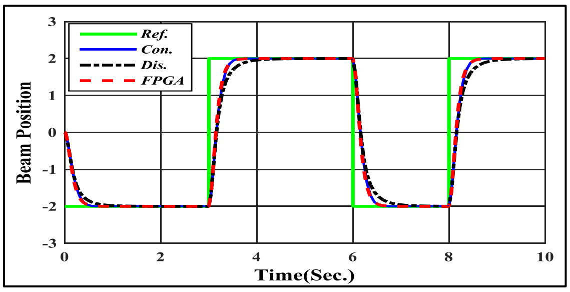


(b)

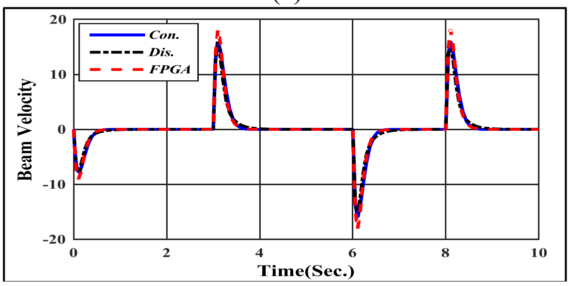


(c)

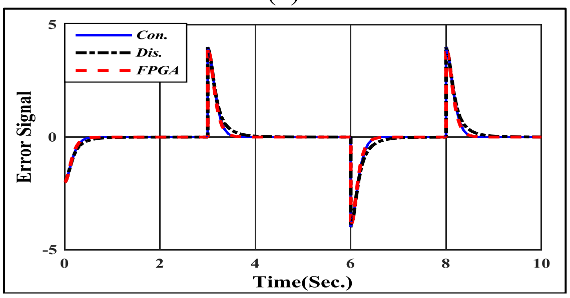
Figure 10: Matlab simulink connection for ball and bean system with PD controller; (a): continuous connection; (b): discrete connection; (c): FPGA connection



(a)



(b)



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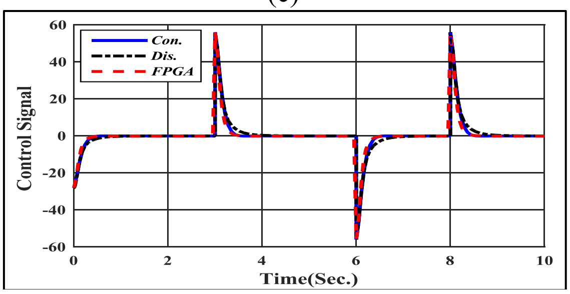


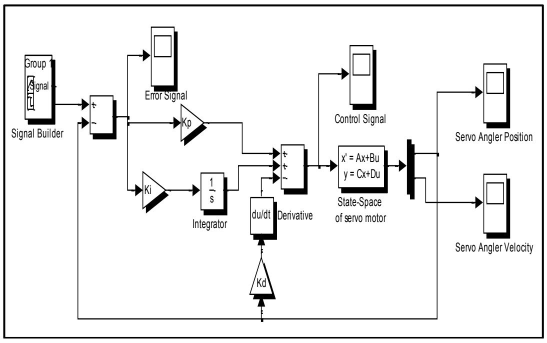
(d)

Figure 11: Simulation results for ball and beam system without servo motor controlled by PD in (continues, discrete, FPGA) form with step input of mag.2: (a) beam position; (b) beam velocity; (c) error signal; (d)control signal

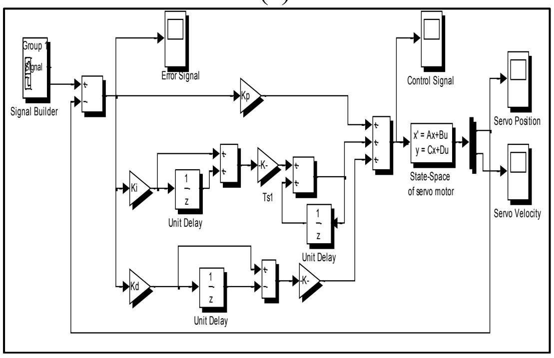
These results show that the beam position follows the desire position for system with continuous, discrete, FPGA PD controller only (with zero steady state error and no overshoot) with suitable control signals.

II. Simulation Results for Servo Motor

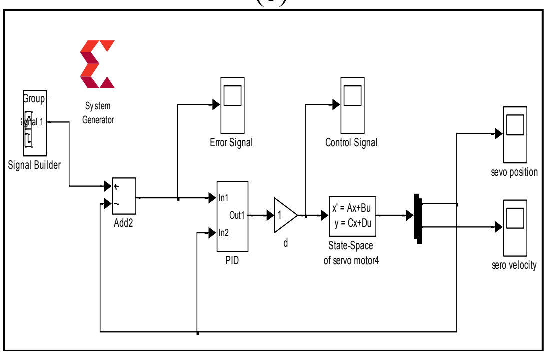
The Matlab simulink diagram for inner loop (servo motor) controller only without ball and beam system is shown in Figure 12, the simulation results for motor position, ball velocity, control signal, and error signal of this diagram are shown in Figure 13.



(a)



(b)



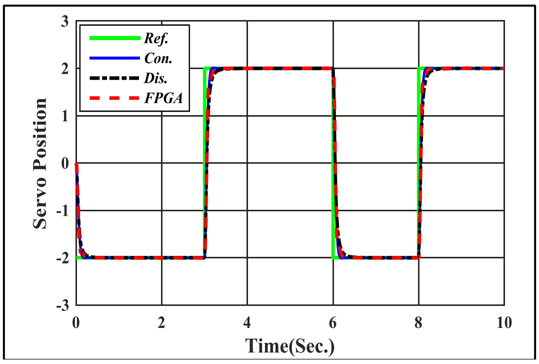
(c)

Figure 12: Matlab simulink connection for servo motor system with PID controller; (a): continuous connection; (b): discrete connection; (c): FPGA connection

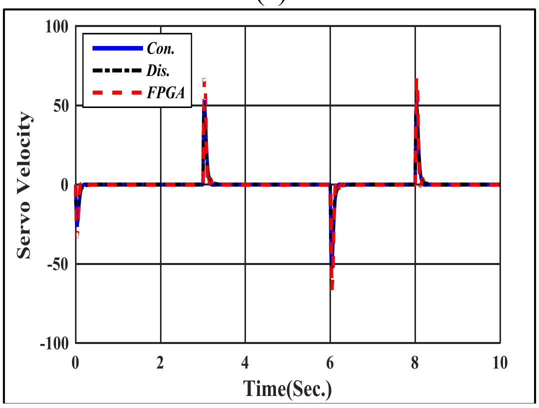
The performance of the controlled servo motor for continues, discrete, and FPGA connection with step input signal with mag.2 are shown in Figure 13. As shown in above figures, the servo motor controlled by the PID follow the desired input very fast with (zero steady state error and no overshot).

III. Simulation and hardware results for complete connection

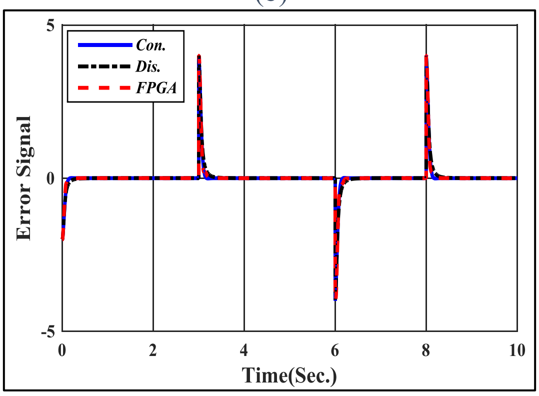
The Matlab Simulink diagram for complete connection (inner servo motor, ball and beam outer loop) with neglect the servo dynamic model for continuous/discrete, FPGA connection are shown in Figure 14, the simulation and hardware results for ball position, ball velocity, control signal, and error signal of these diagram are shown in Figure 15.



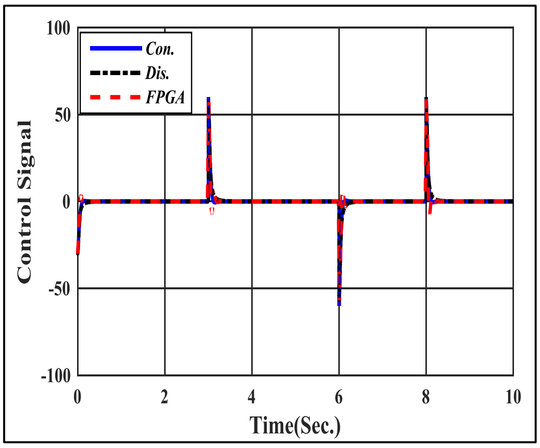
(a)



(b)

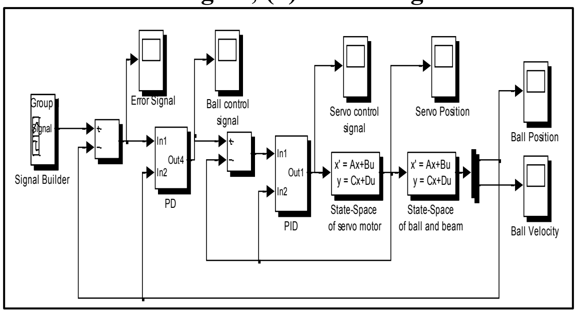


(c)

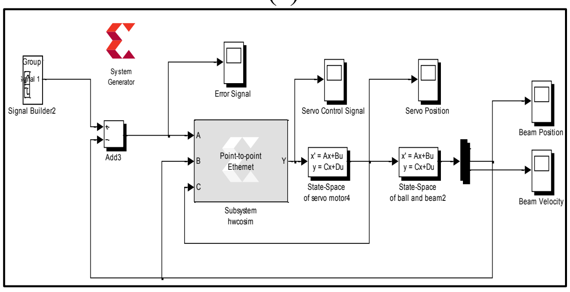


(d)

Figure 13: Simulation results for servo motor system without beam controlled by PID in (continues, discrete, FPGA) form with step input of mag.2: (a) servo position; (b) servo velocity; (c) error signal; (d) control signal

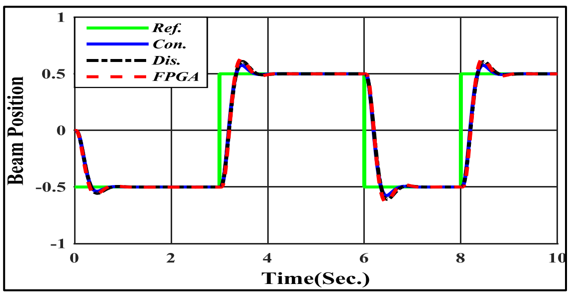


(a)

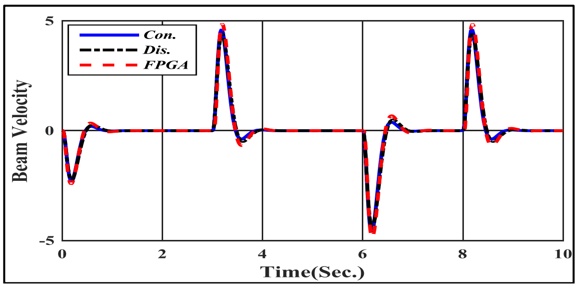


(b)

Figure 14: Matlab simulink connection for complete system connection system with two stage controller; (a): continuous connection; (b): FPGA connection.

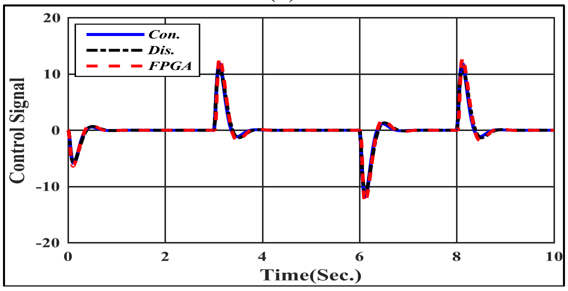


(a)



(b)

(c)



(d)

Figure 15: Simulation and hardware results for complete system (ball and beam system controlled by servo motor) in (continues, discrete, FPGA) form with step input of mag.0.5: (a) beam position; (b) beam velocity; (c) error signal; (d) servo control signal

As shown in Figure 15, the beam and ball system controlled by the two stages follow the desired input very fast with (zero steady state error and overshot due to the effect of connection to controller).

6. Summary and Conclusions

This paper present a simple two stages controller for ball and beam with hardware FPGA design in order to bring the ball to the desired position on beam manipulate by servo motor. The first stage is PID controller for servo motor, while the second stage is PD controller for ball and beam system. The hardware FPGA design for the two-stage controller is implementing by Spartan-3A DSP XA3SD3400A Xilinx kit, the utilization summary of implementation the suggested PD and PID controller show that the maximum frequency allowed for this controller is 14.232 MHz with 1% of hardware platform slices.

Comparative analysis for (continuous/discrete, FPGA connection) are provided by Matlab/Simulink and the simulation results show that the suggested two stages controller satisfy high performance efficiency with fast response and nearly zero steady state error for all continuous/discrete, and FPGA connection.

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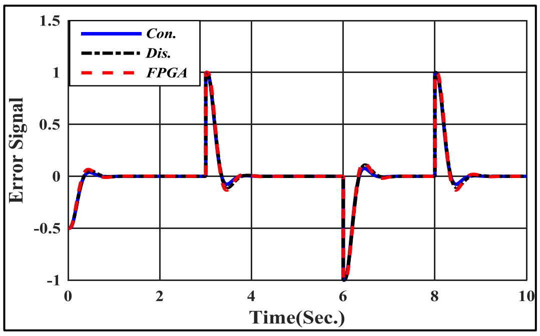

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