FPGA Synthesis of Fuzzy (PD and PID) Controller for Insulin Pumps in Diabetes using Cadence

R. HariKumar, V.K. Sudhaman, C.Ganesh Babu

Abstract*— This paper emphasizes on a FPGA synthesis of Fuzzy PD and PID Controller in biomedical application. We aim at identifying a proper methodology for the infusion process of insulin to diabetic patients using an automated fuzzy logic PD and PID controller. A synthesis of FPGA model of the above automatic controller is analyzed and synthesized. In Type I and Type II diabetes the patient is dependent on an external source of insulin to be infused at an appropriate rate to maintain blood glucose concentration. Hypoglycemia has short term effects which can lead to diabetic coma and possibly death, while hyperglycemia has a long term impact that has been linked to nephropathy, retinopathy and other tissues damage. In this process insulin is administrated through an infusion pump as a single injection. The pump is controlled by the automatic control Fuzzy PD Controller which is more efficient compared to the conventional PD Controller. This is of primary importance where the processes are too complex to be analyzed using the conventional one. The designed controller is implemented with low power multiplier and Fuzzy controller architecture. In case of non- linear inputs, Fuzzy PD Controller performs better compared to the conventional controller and consumes lesser power. The blood glucose level is monitored from Photo Plethysmography of pulse Oximeter. This fuzzy controller model will surely be a boon to the diabetic patients.

***Index Terms*— Fuzzy PD and PID controller, FPGA synthesis, Photo Plethysmography, Insulin pump, Diabetes**

I. INTRODUCTION

In this paper we aim at identifying a proper methodology for the infusion process of insulin to diabetic patients using an automated fuzzy logic PD controller. Diabetes Mellitus is one of the world's most popular diseases which affect approximately one hundred million people worldwide. When a healthy subject has a meal, the blood glucose level can increase around 120-140 mg/dL. Then, pancreas releases insulin and the glucose level decreases to euglycemic level (i.e., 80-100mg/dL)[1]. In absence of insulin release, the glucose level cannot return to euglycemic level. There are two types of diabetes and are Type I and Type II. In this paper the focus is on Type I diabetes. Palo Magni and Ricardo [11] presaged about the recent advances in technology which have brought in noninvasive modes of insulin delivery such as Trans dermal, pulmonary and oral. Even though these modes are not painful like invasive modes, but have problems such as low skin permeability in the Trans dermal mode, not inhaling the accurate amount of insulin in the pulmonary mode and issues concerned with the oral bioavailability for the oral mode.

In this process insulin is administrated through an infusion pump as a single injection. The pump is controlled by the automatic control Fuzzy PD Controller which is more efficient compared to the conventional PD Controller. This is of primary importance where the processes are too complex to be analyzed using the conventional one. In case of non- linear inputs, Fuzzy PD Controller performs better compared to the conventional controller.

II. FUZZY CONTROL SYSTEM

A logical system, which is much closer to the spirit of human thinking and natural language than the traditional logic system is called a Fuzzy logic. Here the Fuzzy Controller is considered as new approach between the conventional mathematical control and human like decision making. A variety of methods have been there in the literature to model the glucose-insulin dynamics. Ackerman et al [12], [13] used a two compartment model to represent the dynamics of glucose and insulin concentration in the blood system. This process is based on compartmental technique. One of the features of this technique is that the model design based on an understanding of the physiology. Hence this model is chosen, as the blood glucose level varies nonlinearly. This is of primary importance where the processes are too complex to be analyzed using the conventional one. In case of non- linear inputs, Fuzzy (PD and PID) Controller performs better compared to the conventional controller.

The task organization for obtaining FPGA Synthesis of Fuzzy PD&PID Controller is as follows:

1. Measurement of Blood glucose level using Photo Plethysmography method.
2. Design of Fuzzy PD controller (2x1) based on error and error rate as inputs and output signal to control the movement of infusion pump.
3. Performance study of conventional PD&PID controller with Fuzzy PD&PID controller.
4. VLSI Design and Simulation of Fuzzy PD &PID Controller are analyzed.
5. FPGA Implementation of Fuzzy PD&PID Controller is analyzed.

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III. SYSTEM ARCHITECTURE

The determination of these Fuzzy sets is normally carried out by initially providing the system with a set of data manually fed by the operator. K.H.Kienitz and T.Yoneyama [4] identified that the Fuzzy system can be further enhanced by the adaptive control where the time constant and gain are varied to self tune the controller at various operating point. The Figure.1 depicts the Fuzzy Control system. The output of Photoglucometer (Photo plethysmography) is converted to digital signal. This signal is compared with set point (sp) and error and rate of change of error is calculated and they are given as an input to the Fuzzy inference Control system. The output u(nT) of the plant is calculated which act as the position control of an insulin pump.

IV. PHOTOGLUCOMETER

In normal practice the level of glucose in blood is found by finger prick and this is done many times day. The Photoglucometer offers a painless alternative; here glucose content is measured without taking blood sample. The infrared radiation is incident on the person’s finger. A portion of light is transmitted through the skin a portion is absorbed and a portion is reflected. The sensor to extract information regarding glucose content in the blood uses the transmitted radiation. This is a simple non invasive sensor for the measurement of blood glucose level. In this instrument, red and infrared light at wavelengths of 640 nm and 940 nm are passed through the finger of the subject and the transmitted light is received with the help of a photo diode and detector discussed in the references [1],[2]. The output of the Photoglucometer obtained is called photoplethysmogram is given to voltage amplifier network and then processed in an Analog to digital converter to give in as the input to the control system. The voltage of the system is graduated by comparing with conventional Glucometer reading.

The figure.2 shows the block diagram of a Photoglucometer and the Photoglucometer output levels are shown in table.I.

Table.I Photo Glucometer Output Levels

S.No.	Blood Glucose Level (mg/dl)	Photoglucometer Output (Volt)	Control levels
1.	50	8	Lower point
2.	100	9	Set point
3.	200	10	Upper point

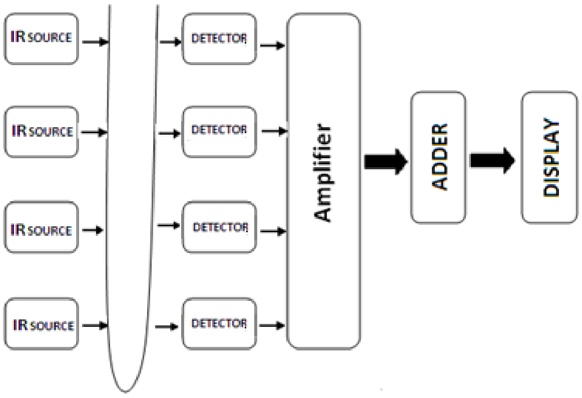

Figure.2 Photoglucometer

A. Analysis of Fuzzy PD Controller

Fuzzy logic control technique has found many successful industrial applications and demonstrated significant performance improvements. In standard procedure the design consists of three main parts Fuzzification, Fuzzy logic rule base, and Defuzzification.

B. Mathematical Models for Blood Glucose Dynamics

Ackerman et al [12] used a two compartment model to represent the dynamics of glucose and insulin concentration in the blood system. C.C.Lim and K.L. Teo [5] mathematically modeled optimum delivery of insulin to the patients based on blood glucose dynamics and the blood Glucose dynamics of an individual can be written as,

$$\dot{x}_1 = -m_1x_1 - m_2x_2 + p(t) \quad (1)$$

$$\dot{x}_2 = -m_3x_2 + m_4x_1 + u(t) \quad (2)$$

where $\dot{x}_1$ represents blood glucose level deviations, $\dot{x}_2$ denotes the net blood glycemic harmonic level, p(t) represents the input rate of infusion of glucose, u(t) denotes the input rates of infusion of insulin and m_1,m_2,and m_3 and m_4 are parameters.

C. Design of Fuzzy PD controller

Baogang et al [3] described that the conventional continuous time PD control law can be written as,

$$u(t) = k_p^c e(t) + k_d^c e(t) \quad (3)$$

Where k_p^c and k_d^c are the proportionality derivative gains of the controller and e(t) is the error signal defined by

$$e(t) = sp(t) - y(t) \quad (4)$$

Sp (t) is the set point and y (t) is the system output.

The Figure.3 depicts the Fuzzy PD Controller with y(nT) the output of Photoglucometer (Photo Plethysmography) which is compared with set point (sp), the error and rate of error are calculated and they are given as an input to the Fuzzy inference system which consists of fuzzifier, rule base and Defuzzification, which produces the control input Δu (nT). The input u (nT) of the plant is calculated which act as the position control of an insulin pump.

By applying the standard conformal mapping, we have

$$u(z) = [k_p + k_d(1 - z^{-1})/(1 + z^{-1})]E(z) \quad (5)$$

Taking inverse z-transform for equation (5) we have

$$\frac{u(nt) + u(nT - T)}{T} = \frac{k_p}{T}[e(nT) + e(nT - T)] + \frac{k_d}{T}[e(nT) + e(nT - T)] \quad (6)$$

Define $$\Delta u(nT) = \frac{u(nT) + u(nT - T)}{T} \quad (7)$$

$$r(nt) = \frac{e(nT) - e(nT - T)}{T} \quad (8)$$

$$d(nT) = \frac{e(nT) + e(nT - T)}{T} \quad (9)$$

Where Δu(nT) ,r(nT) and d(nT) are the incremental control , the rate of change and the average of change of the error signal respectively .

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Substituting (7), (8), (9) in (6) gives

$$\Delta u(nT) = k_p d(nT) + k_d r(nT) \qquad (10)$$

Where k_p and k_d defined by $k_p = k_p^c$ and

$k_d = (2/T) k_d^c$.

Based on the membership functions as shown in figure 4, the fuzzy control rules that we used are the following

Fr1: IF error = ep AND rate = rp THEN output = oz
Fr2: IF error = ep AND rate = rn THEN output =op
Fr3: IF error = en AND rate = rp THEN output =on
Fr4: IF error = en AND rate = rn THEN output = oz

Here the output is the fuzzy control action Δu (nT), ep means error positive and oz means output zero etc., and the "AND" is the Zadeh's logical AND defined by, μ_A AND μ_B = min { $\mu_A . \mu_B$ } for any two membership values μ_A and μ_B on the fuzzy subsets A and B respectively. In the defuzzification center of mass formula is employed [13]

$$\Delta u(nT) = \frac{rp \times oz + rn \times op + en \times on + en \times oz}{rp + rn + en + en} \qquad (13)$$

We use op = 2; on = -3; z=0

Figure.5 indicates the step response of optimal PD and Fuzzy PD system. Fuzzy PD controller performs better than conventional PD controller. The designed controller is simulated in MATLAB and the results are obtained.

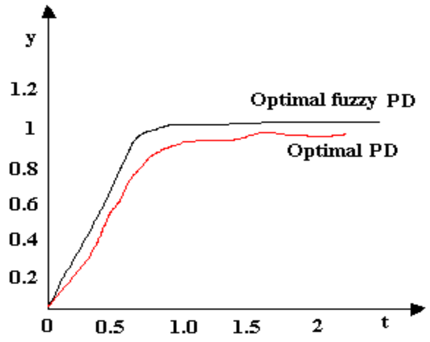


Figure.5 Step responses of optimal PD and optimal fuzzy PD controllers

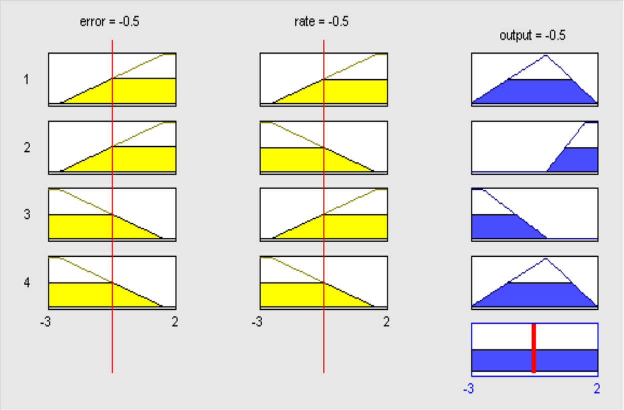


Figure.6 Rule base of Fuzzy PD simulated in MATLAB

Figure 6 and 7 Shows the MATLAB simulated fuzzy Rule base and the Controller control surface respectively.

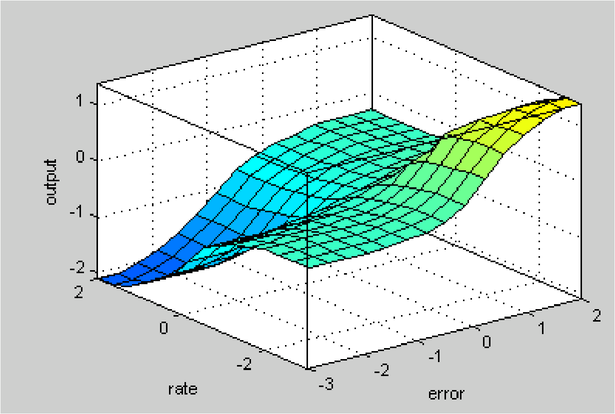


Figure.7 Control surface of Fuzzy PD simulated in MATLAB

D. Design of Fuzzy PID controller

The block diagram of Fuzzy PID controller is depicted in figure.8.The Fuzzy PID controller e (t) is the error signal defined by [7]

$$e(t) = sp(t) - y(t) \qquad (14)$$

Sp (t) is the set point and y (t) is the system output.
r (nT) is the rate of change of error signal defined by

$$r(nt) = \frac{e(nT) - e(nT - T)}{T} \qquad (15)$$

The controller output (control input to a plant) is denoted by u (n). B.Hu et al [6]described that the scaled discrete-time output $u(\hat{t})$ is the sum of three terms as shown in Fig.4 and is represented by

$$\hat{u}(n) = \hat{K}_P * \hat{u}_p(n) + \hat{K}_I \sum_{i=0}^{n} \hat{u}_p(i) + \hat{K}_D * \frac{\Delta \hat{u}_p(n)}{\Delta t} \qquad (16)$$

We define $\hat{u}_p$ as a defuzzified proportional output; and its change is $\Delta \hat{u}_p (\Delta \hat{u}_p(0) = 0)$ for the sampling period Δt.

$\hat{K}_P, \hat{K}_I, \hat{K}_D$ Are the normalized proportional, integral, and derivative gains, respectively. They are all normalized within a range of [0, 1].

From the membership functions, the following fuzzy control rules [8] are used as shown below,

R1: IF error = PB AND rate = PB THEN output = AZ
R2: IF error = PB AND rate = AZ THEN output = PB
R3: IF error = NB AND rate = NB THEN output = AZ
R4: IF error = NB AND rate = AZ THEN output = NB
R5: IF error = AZ AND rate = NB THEN output = NB
R6: IF error = AZ AND rate = AZ THEN output = AZ
R7: IF error = AZ AND rate = PB THEN output = PB

The membership functions for error, rate, and output signal are shown in Fig.9

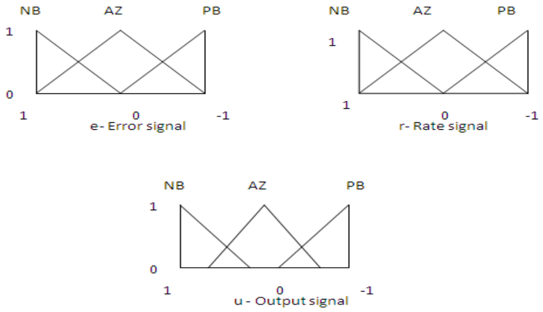


Figure.9 Membership functions of a fuzzy PID controller

Where e is the scaled error signal. The fuzzy variable "NB" stands for "*negative big*", "PB" for "*positive big*" and "AZ" for "*approximate zero*". For simplicity, we use triangular membership functions. While the membership functions for error signal and rate signal are fixed, the membership functions for output signal may be changed.

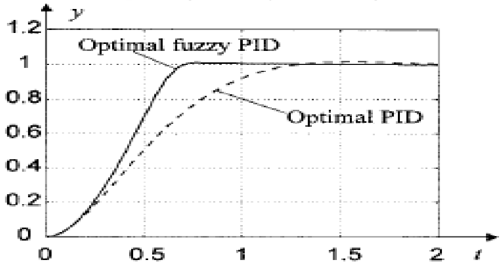


Figure.10 Step responses of optimal PID and optimal fuzzy PID controller

Figure.10 depicts the step response of optimal PID and Fuzzy PID controller. Fuzzy PID controller performs better than conventional PID controller.

V. VLSI DESIGN OF FUZZY PROCESSOR

VLSI architecture is designed to implement the fuzzy based controller for insulin pumps in diabetic patients. This implementation aims at improvement of speed and efficiency of the system. The design developed here was that of a low cost, high performance fuzzy processor with two inputs and a single control output. As shown in figure.11, the block diagram of VLSI Architecture of Fuzzy Controller has an error generator, fuzzy controller, output control signal and the process of infusion being carried on by the insulin pump in a single injection process. In this work the fuzzy architecture is implemented and simulated using VHDL which is IEEE standard language for both simulation and synthesis. VLSI system is incorporated using VHDL Design unit called Process. The simulation results of Fuzzy PD Controller Output for Photoglucometer Set (-3, 2) shown in Table II. The simulation results of Fuzzy PID Controller Output for Photoglucometer Set (-1, 1) shown in Table III.

Table.II Fuzzy PD Controller Output Levels For Photoglucometer Set (-3, 2)

Sno.	Inputs		Outputs
	Error	Rate	Fuzzy Control Output
1	0.364	0.761	0
2	0.727	0.945	0
3	1	1.3	0
4	1.4	1.6	0
5	2	2	0
6	0.45	-0.201	0.961
7	0.727	-0.66	1
8	1.14	-1.07	1
9	1.59	-2.91	1
10	1.86	-2.91	1
11	-0.273	0.349	-1.48
12	-0.727	0.67	-1.5
13	-1.41	0.942	-1.5
14	-2.18	1.22	-1.5
15	-3	2	-1.5
16	-0.5	-0.58	0

Table II and Table III indicate the simulation of Fuzzy PD and PID controller for different input conditions. From this set of simulated conditions it is identified that all the rules in the rule base are working perfectly. There is no gray region at the output even though the inputs are overlapped in the linguistic sets.

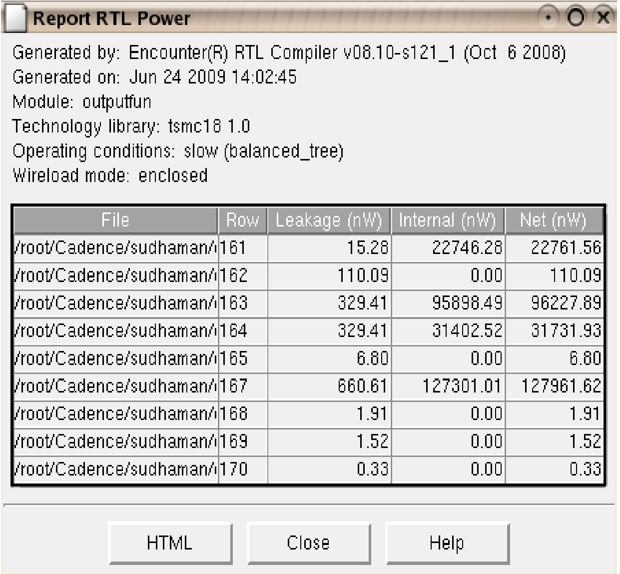
Table.III Fuzzy PID Controller Output For Photoglucometer Set (-1, 1)

S no.	Inputs		Outputs
	Error	Rate	Fuzzy Control Output
1	0.364	0.761	0
2	0.727	0	0.727
3	-0.12	0	-0.12
4	0	-0.165	-0.165
5	0	0	0
6	0	0.66	0.66
7	0.986	0.123	0
8	-0.154	-0.987	0
9	0.35	0	0.35
10	-0.273	-0.349	0

VI. FPGA IMPLEMENTATION AND SYNTHESIS IN CADENCE

The designed control system in coded in VHDL and Implemented in Cadence EDA too l [14],[15]. It is compiled in NC SIM and simulated in SIM vision for functional verification and the output of the system in wave form is as shown in Figure 12.The System is then synthesized in Cadence encounter RTL Compiler Ultra and the schematic RTL viewer is as shown in figure.13.

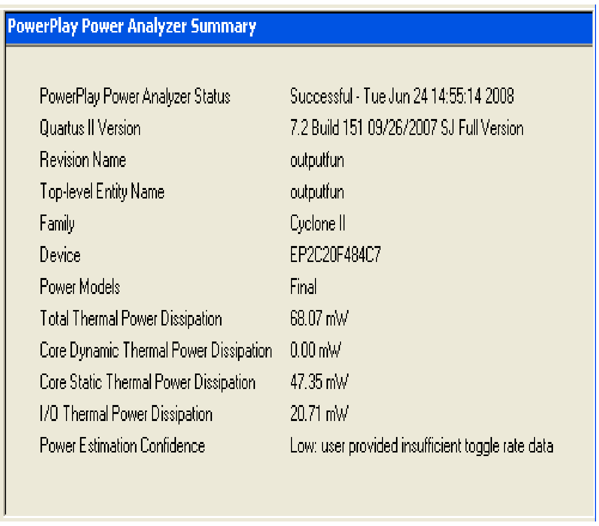
The power utilization of the design in cadence is given below in Figure.14.It reveals that lesser power that the Altera Cyclone II FPGA [9] in figure.15 .The Power consumed in Cadence is of the range of 22.761uw (22761.56 nw) whereas in Altera FPGA 68uw.The system implemented in cadence consumes lesser power than the one implemented in Altera cyclone II FPGA.



Generated by: Encounter(R) RTL Compiler v08.10-s121_1 (Oct 6 2008)
Generated on: Jun 24 2009 14:02:45
Module: outputfun
Technology library: tsmc18 1.0
Operating conditions: slow (balanced_tree)
Wireload mode: enclosed

File	Row	Leakage (nW)	Internal (nW)	Net (nW)
/root/Cadence/sudhaman/	161	15.28	22746.28	22761.56
/root/Cadence/sudhaman/	162	110.09	0.00	110.09
/root/Cadence/sudhaman/	163	329.41	95898.49	96227.89
/root/Cadence/sudhaman/	164	329.41	31402.52	31731.93
/root/Cadence/sudhaman/	165	6.80	0.00	6.80
/root/Cadence/sudhaman/	167	660.61	127301.01	127961.62
/root/Cadence/sudhaman/	168	1.91	0.00	1.91
/root/Cadence/sudhaman/	169	1.52	0.00	1.52
/root/Cadence/sudhaman/	170	0.33	0.00	0.33

Figure.14 Power Usage report in cadence



PowerPlay Power Analyzer Status	Successful - Tue Jun 24 14:55:14 2008
Quartus II Version	7.2 Build 151 09/26/2007 SJ Full Version
Revision Name	outputfun
Top-level Entity Name	outputfun
Family	Cyclone II
Device	EP2C20F484C7
Power Models	Final
Total Thermal Power Dissipation	68.07 mW
Core Dynamic Thermal Power Dissipation	0.00 mW
Core Static Thermal Power Dissipation	47.35 mW
I/O Thermal Power Dissipation	20.71 mW
Power Estimation Confidence	Low: user provided insufficient toggle rate data

Figure.15 Power Estimation in Altera Quatrus II Power Play tool

VII. RESULTS AND DISCUSSION

A logical system, which is much closer to the spirit of human thinking and natural language than the traditional logic system is called a Fuzzy logic. Here the Fuzzy Controller is considered as a new rapprochement between the conventional mathematical control and human like decision making. The Fuzzy controller has to be provided with a pre-defined range of control parameters or sense of fields. The determination of these sets is normally carried out by initially providing the system with a set of data manually fed by the operator. The Fuzzy system can be further enhanced by the adaptive control where the time constant and gain are varied to self tune the controller at various operating points.

The architecture is simulated with various values of error and error rate values. The initial conditions for the overall control systems have the following natural values. For the fuzzy control action $\Delta U(0)=0$; for the system output y (0) =0and for the original error and rate signals e(0)=r (the set point) and r(0)=r respectively. For our diabetic pump which is a second order system , the transfer function is $H(S)=\frac{1}{s^2+s+1}$. we remark that the Fuzzy PD controller designed above has a self-tuning control capability i.e., when the tracking error e(nT) keeps increasing, the term d(nT)=[e(nT)+e(nT-T)]/T becomes larger. In this case the fuzzy control action $\Delta u(nT)$ also keeps increasing accordingly, which will continuously reduce the tracking error. Under the steady-state condition $|d(nT)|=0$, we found that the control performance of the Fuzzy PD controller in VLSI Simulation is also as good as, if not better than the conventional controller.

This project synthesized in Cadence EDA tool reveal that Power consumed in Cadence simulation is of the range of 22.761uw (22761.56 nw) whereas in Altera FPGA 68uw.This shows that the designed system in cadence EDA consumes lesser power than a controller in FPGA .

VIII. CONCLUSION

The simulation results have shown that this Fuzzy PD Controller overrides the conventional controller in handling non-linear inputs. In this project it is assumed that the patient is continuously attached to the infusion pump and the blood glucose level is monitored at regular intervals. The designed controller is simulated and the result shows that the Fuzzy controller performs better than the conventional Controllers in handling nonlinear inputs to the system. The designed controller has self tuning capability that over comes tracking error. In this project Insulin is administered to diabetic patients with Type I Diabetes using an automated Fuzzy (PD and PID) Controller system. The control system consists of Photoglucometer and an insulin pump. This controller is a closed loop system not requiring a prior reference of blood glucose content. The simulation results have shown that this Fuzzy PD, PID Controller overrides the conventional controller in handling non-linear inputs. In this work it is assumed that the patient is continuously attached to the infusion pump and the blood glucose level is monitored at regular intervals. Further research can be in the direction of implementing an Application Specific IC (ASIC) fuzzy controller for Insulin pumps.

ACKNOWLEDGEMENTS

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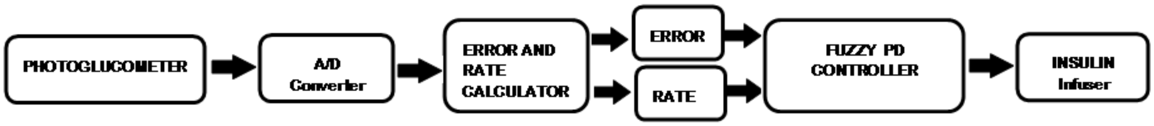

Figure.1 Model of Fuzzy Control System

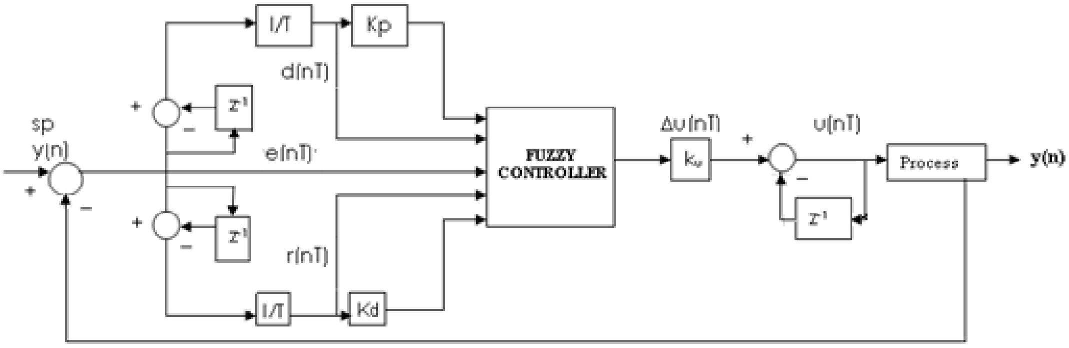

Figure.3 Fuzzy PD controller system

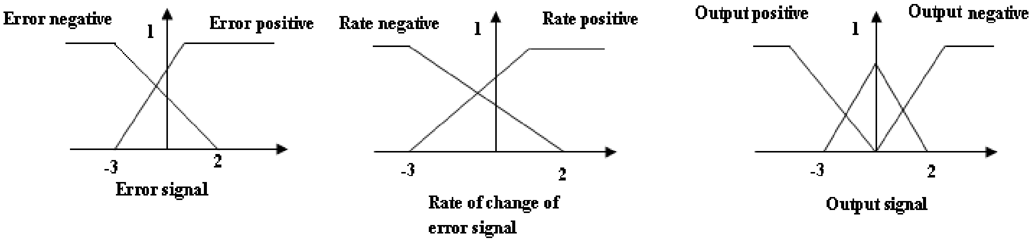

Figure.4 The membership function of e (nT), r (nT) and u (nT)

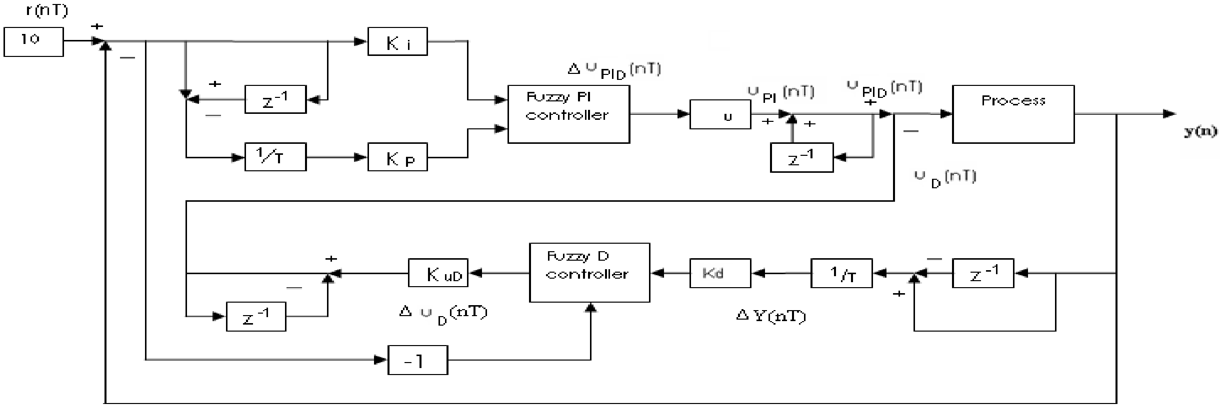

Figure.8 Fuzzy PID controller

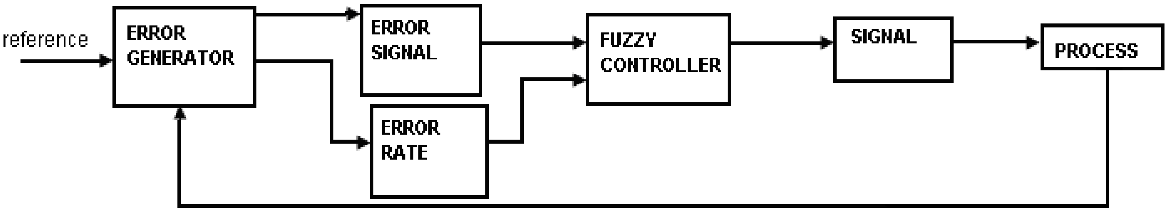

Figure.11 VLSI Architecture of Fuzzy Controller

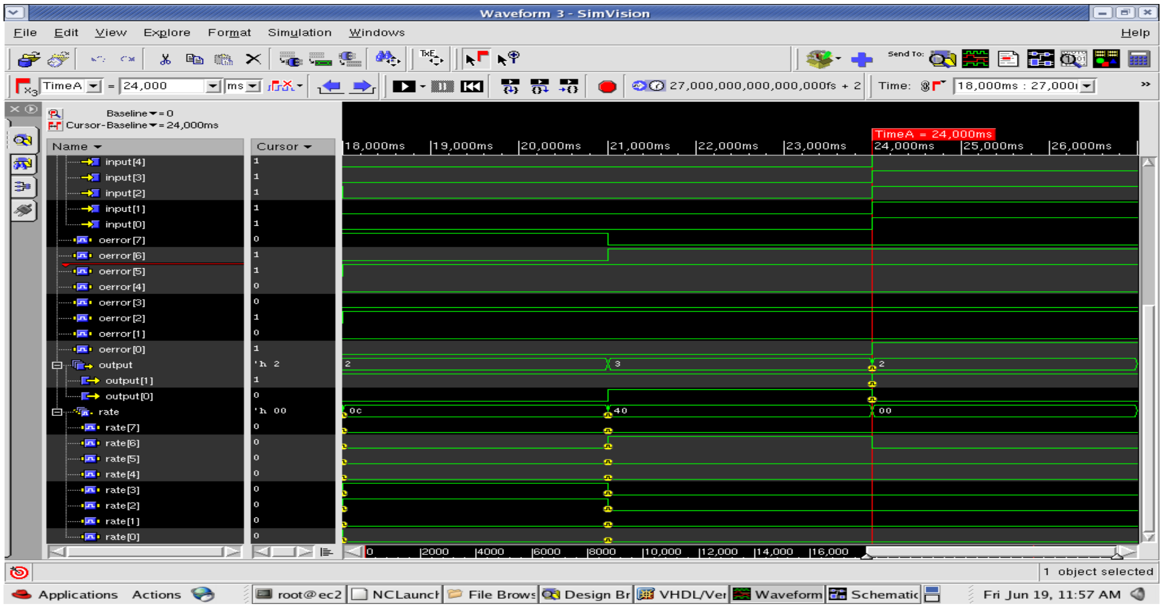

Figure.12 Waveform Simulation of PD controller in Cadence NC sim

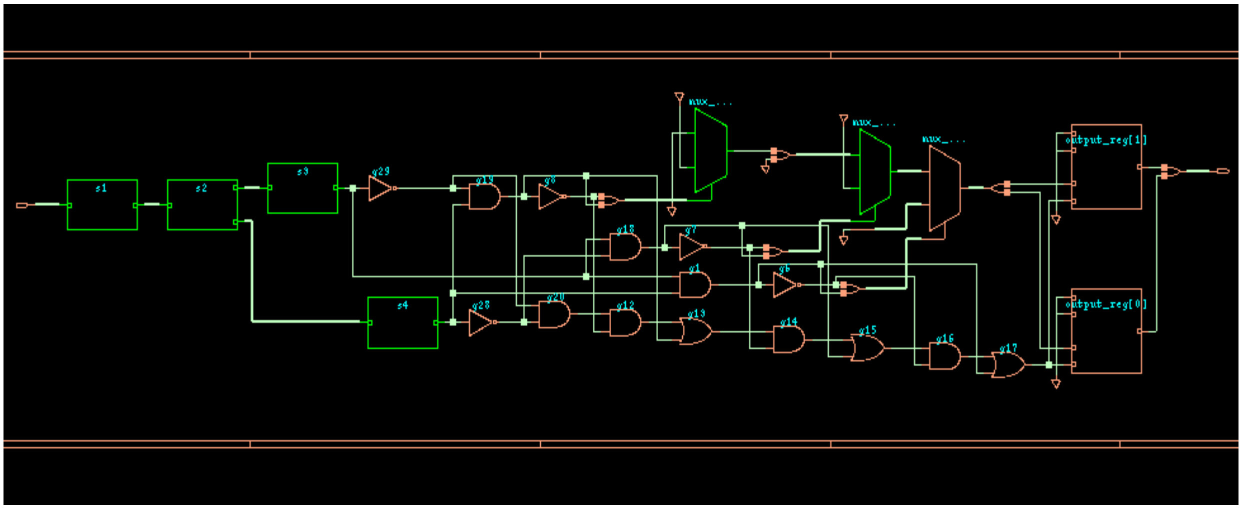

Figure.13 Cadence RTL net list simulation