Controlling of Rotary Inverted Pendulum with Self-Tune Fuzzy PID

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Abstract: Inverted pendulum is a widely used mechanism in designing of robotic arm. The aim of this research is to model a self-tuned hybrid fuzzy logic (P+D & fuzzy) controller for inverted-pendulum; real time parameters are used in NI Lab-View software, for its proper modeling and controlling. This self-tuned PD works on error and is sent to computer-based model to generate suitable output for pendulum. The microcontroller-based interface gets input from rotational inverted pendulum; as per difference in error movement is updated via feedback signal of rotational angle measured by optical encoder until the stable position is achieved. The parameters of PD are set by self-tuning algorithm. Thus, the comparative analysis with previous work concludes that the research is very helpful for implementing the concept in self-stabilizing robots.

Keywords: *Inverted pendulum, PD control, Self-tuned fuzzy controller, Lab-View, Stability.*

1. Introduction

Inverted pendulum is a 2D oscillating rotational inverted pendulum with two independent motions (DOF- Degrees Of Freedoms). Robotic inverted pendulum's angle along with forward and reverse direction is a conventional way to deploy input control to stabilize an unbalanced pendulum. The arrangement of prototype is depicted in Figure 1[1-2].

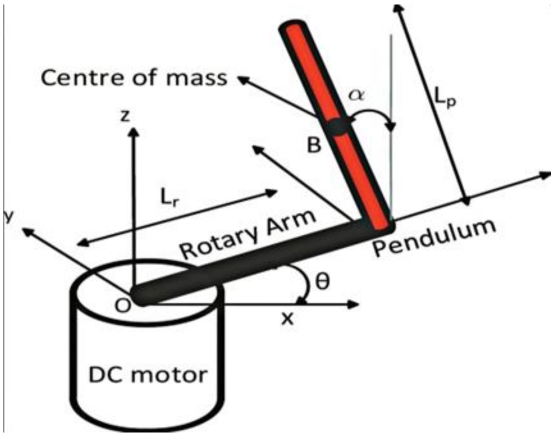

Figure.1. Block Diagram of Inverted Pendulum [5].

Thus, as per evaluation done by numerous analysts; a typical control criteria for the examination of programmed control strategies the linearizing techniques are made effective at large portion for control design. Objectives of this research work are controlling swing-up and balancing; a standard controller fuzzy+P is designed for swing-up whereas fuzzy +PD for balancing. The narrow steel pole of the pendulum with pivoted base, indicated as rotate point, is mounted on a heading. The diversion of the pendulum rotational angle (α) and arm angle (θ) moves on a level plane with a specific end goal for stabilizing the pendulum. A Proportional-Derivative PD fuzzy controller is utilized to balance the pendulum to the equilibrium state. The zero-reference point of pendulum's pole is connected to one of the main encoder i.e. potentiometer (pot) of the model. Accordingly, due to varying positions, different voltages are produced that are compared to zero reference point voltage. Therefore, a proper control signal is generated.

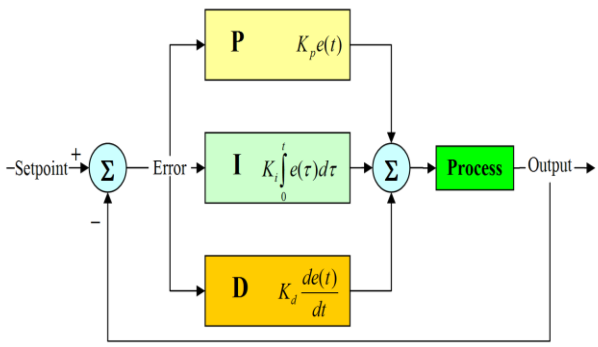

Figure.2. Block Diagram of PID Controller [8].

The Lab-View has been utilized for testing and recreation of positions with various estimations of proportional gain (*Kp*) and differential gain (*Kd*). Fuzzy logic depends on four essential parameters: fuzzy sets, possibility distributions, linguistic variables and fuzzy if-then principles. Fuzzy sets are sets with uncertain limits/boundaries.[3] Factors concerned to linguistic are

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characterized by a fuzzy set. In addition, probability distributions are limitations on linguistic factors set up by fuzzy set. Fuzzy if-then principles are rules that sum up a intimation in two-esteemed logic.

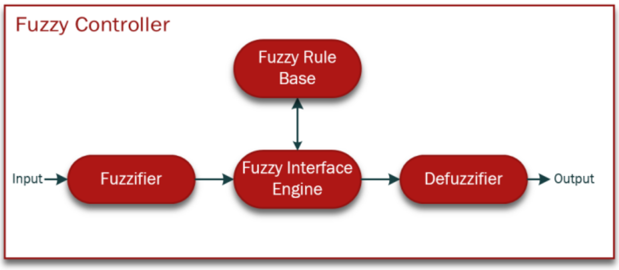

Figure.3. Block Diagram of Fuzzy Logic [12].

Fuzzy sets enable fractional membership to various sets, unlike traditional sets where components associated with just a single set or the other. In fuzzy sets, membership involves degree which is indicated by a number somewhere in the range of 0 and 1[6]. Here, if element not in the set means 0 on the other hand 1 means element completely in set. The inverted pendulum works on the Newton's Third law of motion.

1.1 Potential Energy: (P.E)

$\boldsymbol{y_p}$ is used to find the potential energy, U_t:

$$U_t(\alpha) = M_p\ gL_p(1 - \cos(\alpha(t))\ ) \qquad (1)$$

Pendulum position at down word position, α = 0, U_t(α = 0) = 0J Pendulum is at the upright position, α = π, U_t (α = π) = *Mp g Lp*

1.2 Kinetic Energy: (K.E)

T_t is used for pendulum rotation.

$$T_t = \frac{1}{2} J_p\ \dot{\alpha}^{\ 2} \qquad (2)$$

Where $\dot{\alpha}$ is rotational velocity of inverted pendulum.

1.3 Pendulum Inertial Movement

To find out inertia frequency of pendulum. when swing freely so, [2].

$$T_p = 0, \quad \alpha = 0 \qquad (3)$$

The set-up equation is non-liner, to linearize the equation sin $(\alpha) =\ \alpha$ when the small value of α.

$$J_p\ (\ddot{\alpha}\ ) + M_p\ g\ L_p\ \alpha = 0 \qquad (4)$$

To solve the linearized equation, use the following initial condition.

$$\alpha\ (0) = \alpha_0 \qquad (5)$$

$$\dot{\alpha}\ (0) = 0 \qquad (6)$$

then, the Laplace transform of the linearized equation:

$$J_p\ (s^2\alpha(s)\text{-}\alpha_0)\text{+}M_g gL_p\alpha(s) = 0 \qquad (7)$$

$$\alpha(s) = \frac{\alpha_0 J_p}{M_p g L_p s\text{+ } J_p s^2} \qquad (8)$$

Therefore, the frequency f

$$f = 2\pi \sqrt{\frac{M_p\ g\ L_p}{J_p}} \qquad (9)$$

Rearranging equation (7) we get moment of inertia J_p:

$$J_p = \frac{M_p\ g\ L_p}{4\ \pi^2 f^2} \qquad (10)$$

2. Methodology

Main QNET Rotary pendulum features and parameters involved in this research work are given in Table 1:

- Full rotational servo system for NI ELVISII(+).
- 18-Volt direct drive brushed DC motor.
- 12-volt encoder scale for Direct Current (DC) motor and pendulum.
- Built-in Pulse Width Modulation (PWM) amplifier.
- Built-in Peripheral Component Interface (PCI) connector for NI ELVISII (+).

2.1 DC Motor: The QNET Rotary pendulum incorporates a direct drive 18 V brushed coreless DC motor model 16705 attached in a strong aluminum outline.

2.2 Encoders: The encoders attached for positional information of dc motor and pendulum of QNET Rotary pendulum are single-finished optical shaft encoders having line count of 512 lines/rev (Yield 2048 lines/rev in quadrature mode). The encoders quantify the precise position of motor and pendulum of the QNET Rotary inverted pendulum. These are Digital (E8P-512-118) single-finished optical shaft encoder.

2.3 Power Amplifier: QNET Rotary pendulum circuit board incorporates a PWM voltage-controlled power amplifier rated 2A peak current and 0.5A constant current (dependent on the Maximum current rating of the motor). The output voltage is ranging between ±10v.

Table 1. Rotary Inverted Pendulum Specification.

Symbol	Description	Value
DC Motor		
Vnom	NOMINAL VOLTAGE	18.1 V
Tnom	NOMINAL TORQUE	22.1 mnm
Wnom	NOMINAL SPEED	3051 rpm
Inom	NOMINAL SPEED	0.541 a
Rm	TERMINAL RESISTANCE	8.40
Kt	TORQUE CONSTANT	0.043 nm/a
Jp	PENDULUM MOMENT OF INERTIA.	1.88 Kg.m^2
G	GRAVITATIONAL ACCELERATION CONSTANT	9.8 m/s^2
Km	MOTOR BACK EMF	0.043 v/(rad/s)
Jm	ROTO INERTIA	4.1×10^{-6} kgm^2
Lm	ROTORINDUCTANCE	1.17mh
Mh	MODULE ATTACHEMENT HUB MASS	0.017 kg
Rh	. MODULE ATTACHEMENT HUB RADIOUS	0.0112 m
Jh	. MODULE ATTACHEMENT MONENT	0.7×10^{-6} kgm2
Rotary Pendulum Module		
M_r	ARM MASS	0.096 kg
L_r	ARM LENGTH	0.086 m
M_p	PENDULUM LINK MASS	0.023 kg
L_p	PENDULUM LINK LENGTH	0.128 m
Motor and Pendulum Encoders		
	ENCODER LINE COUNT	512 lines/rev
	ENCODER LINE COUNT IN QUADRATURE	2048 lines/rev
	ENCODER RESOULTION QUADRATURE	0.177 deg /count
Amplifiers		
	AMPLIFIER TYPE	Pulse Width Mod
	PEAK CURRENT	2.56
	CONTINUOUS CURRENT	0.56
	OUTPUT VOLTAGE	±24v to (±10v)

After the structure is exhibited, the controller can be arranged. In any case, the swing-up controller registers the torque that is associated with a pendulum base arm with the objective that the inverted pendulum will be turned upwards[9]. When the pendulum is swing-up to a particular range about its upright vertical angle using the swing-up controller, the balance controller expect control to balance the pendulum in Figure 12. Overall, a control switch designed in Lab-View will generate a proper signal for stabilizing inverted pendulum as shown in Figure 4. Here, U1(t) and U2(t) are signals from swing-up & balance controller Whereas, U(t) is combined controlled signal.

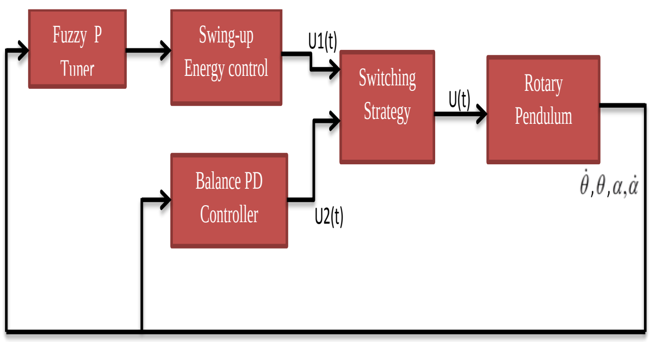

Figure.4. Block Diagram of Swing up Controller [4].

The Rotary pendulum system is depicted in Figure 5 that shows the complete pendulum system in block diagram.

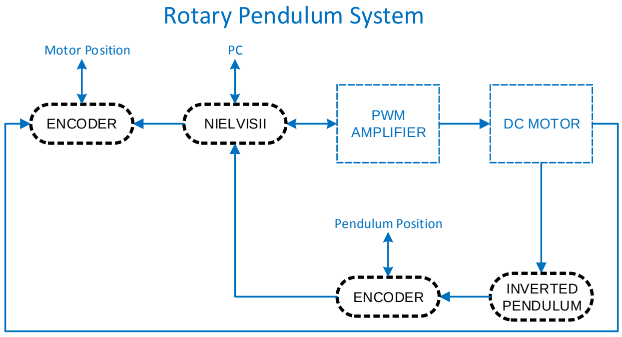

Figure.5. Rotary Pendulum System [5].

It is to be noted in Figure 4 for fuzzy swing-up controller input quantity is energy (E) while output is gain (μ). The objective of fuzzy P controller is to generate an initial thrust when pendulum is downwards; in result appropriate gains are achieved at output. Accordingly, input quantities for PD + fuzzy controller are pendulum's angle (α) and angular velocity ($\dot{\alpha}$) that owes output quantity proportional gain($k_{p,a}$). Here, small power is given to DC motor by balancing controller when pendulum angle and angular velocity are negative or positive. If angel is negative and angular velocity is positive or vice versa the gain will be supplementary.

3. Results and Discussion

The execution of control strategy discussed in this research obviously involves hardware i.e. QNET 2.0 Rotary Pendulum as indicated in Figure 6. On the very first, compatibility interface is built between NI Lab-view and hardware once all set, data is read form sensors to make system states α, $\dot{\alpha}$, θ, $\dot{\theta}$. These states are then feed up to control switch for determining which controller is needed whether balance or swing in result, equilibrium is achieved. Figure 7 shows Lab-View model of reading sensor data and measuring quantities arm angle (α in deg) and link angle (θ in deg) by digital scopes. Moreover, Figure 8 and 9 signify Lab-View sub-system of Swing controller and balancing controller.

Figure 6. Rotary Inverted Pendulum Kit.

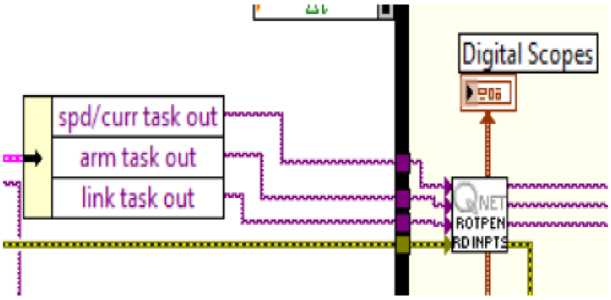

Figure 7. Reading Sensor Data in Lab-view.

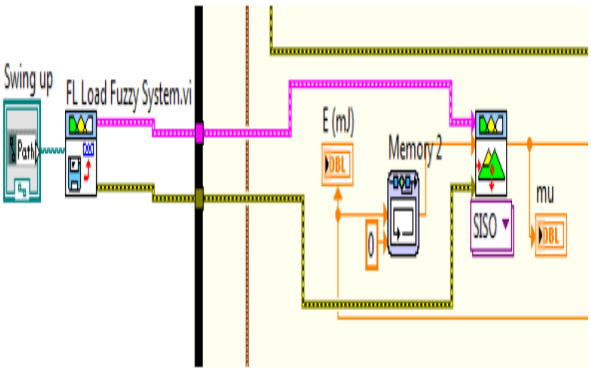

Figure 8. Swing up Control in Lab-View.

The Lab-view subsystem model of fuzzy swing controller along with energy, memory and SISO block is depicted in Figure 8. Whereas in figure 9 fuzzy balancing controller is displayed having input of four parameters α, $\dot{\alpha}$, θ, $\dot{\theta}$. along with MISO and gain blocks.

It can be analyzed the of fuzzy VI controller's output and $k_{p\propto}$ is joined with other parameters and then amplified by gain block.

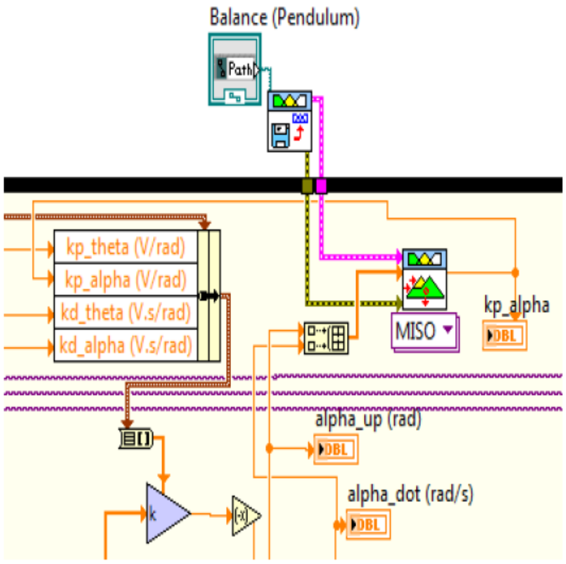

Figure 9. Balance Control in Lab-view.

The values achieved are processed by control switch shown in figure 10 that has a intelligence to decide which controller should be triggred for proper stablizing inverted pendulum.

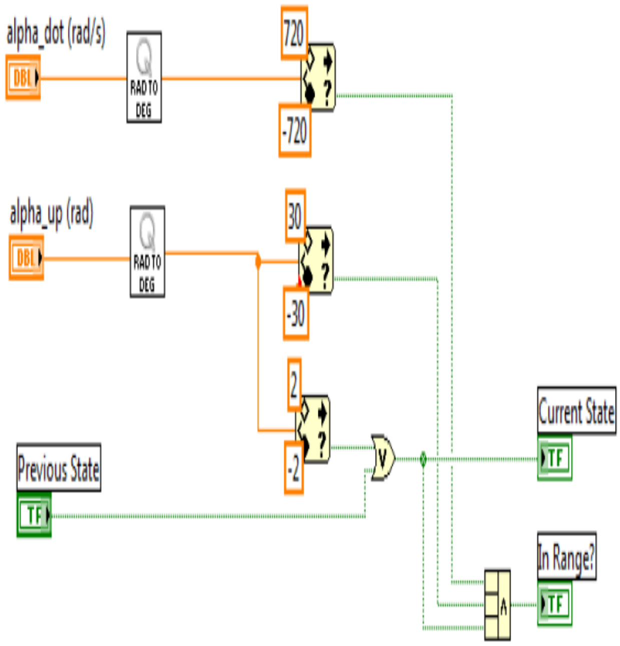

Figure.10. Lab-view Code for Control Switch.

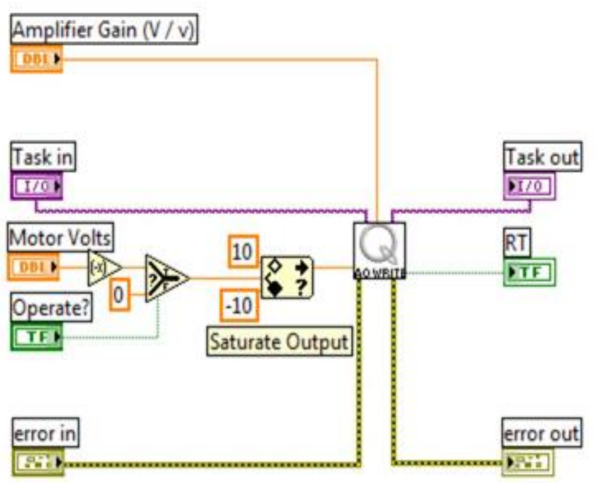

Figure 11. Voltage signal for DC motor Lab-View model.

Energy is calculated by swing controller model, then taken to next step for estimating appropriate linear acceleration so that the pendulum comes in upright position having voltage output for DC motor in last[10-11]. Figure 11 denotes the model to transfer proper conditioned voltage signal either from balance controller or swing-up controller to DC motor.

When all Lab-View sub systems are connected the final model is depicted in Figure 12 perform all objectives of this research.

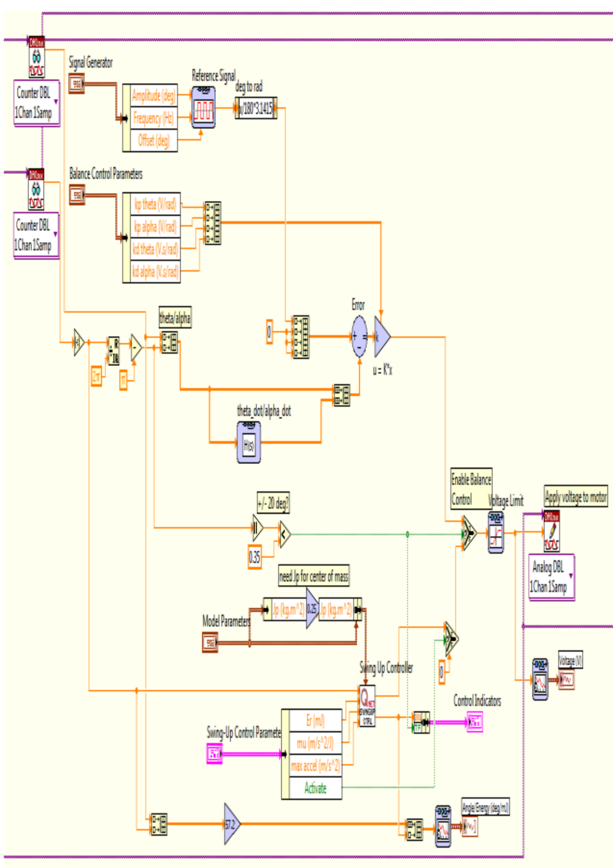

Figure.12. PD Controller in Lab-view

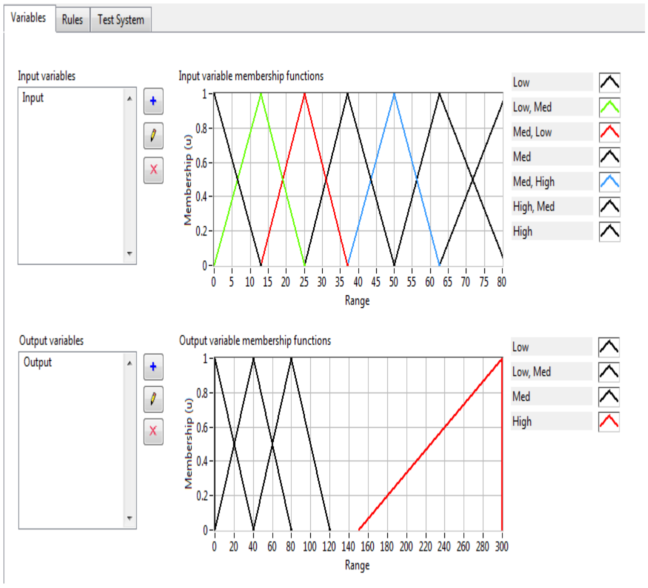

Figure.13. Fuzzy input/output for Swing up Model.

Table.2 Fuzzy If- then rule for Swing-up controller.

1)	If E is 'Low' then μ is 'High'.
2)	If E is 'LowMed' then μ is 'Med'.
3)	If E is 'MedLow' then μ is 'Med'.
4)	If E is 'Med' then μ is 'LowMed'.
5)	If E is 'MedHigh' then μ is 'LowMed'.
6)	If E is 'HighMed' then μ is 'LowMed'.
7)	If E is 'High' then μ is 'Low'.

Note: E is Energy of Pendulum and μ is proportional gain.

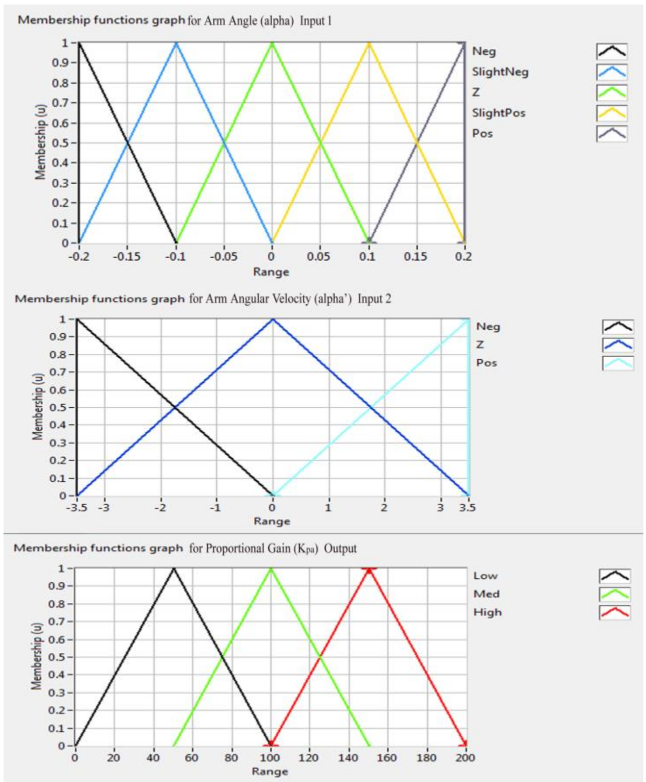

Figure.14. Fuzzy input/output for Balancing Model.

Table.3 Fuzzy If- then rule for Balancing controller.

1)	If α is'Z' and $\dot{\alpha}$ is'Z' and 'Z' , then $k_{p\propto}$ is 'High'.
2)	If α is 'Neg' and $\dot{\alpha}$ is 'Z', then $k_{p\propto}$ is 'Med'.
3)	If α is 'Neg' and $\dot{\alpha}$ is 'Pos', then $k_{p\propto}$ is 'High'.
4)	If α is 'Neg' and $\dot{\alpha}$ is 'Neg', then $k_{p\propto}$ is 'Low'.
5)	If α is'Slight Neg'and $\dot{\alpha}$ is 'Z', then $k_{p\propto}$ is 'Med'.
6)	If α is'Slight Neg'and $\dot{\alpha}$ is'Pos',then $k_{p\propto}$ is 'High'
7)	If α is'Slight Neg'and $\dot{\alpha}$ is'Neg',then $k_{p\propto}$ is 'Med'
8)	If α is 'Slight Pos' and $\dot{\alpha}$ is 'Z' , then $k_{p\propto}$ is 'Med'
9)	If α is'Slight Pos'and $\dot{\alpha}$ is'Pos', then $k_{p\propto}$ is 'Med'
10)	If α is'Slight Pos'and $\dot{\alpha}$ is'Pos' , then $k_{p\propto}$ is 'Med'
11)	If α is 'Pos' and $\dot{\alpha}$ is 'Z', then $k_{p\propto}$ is 'Med'.
12)	If α is 'Pos' and $\dot{\alpha}$ is 'Pos', then $k_{p\propto}$ is 'Low'.
13)	If α is 'Pos' and $\dot{\alpha}$ is 'Neg', then $k_{p\propto}$ is 'High'.

Note: α is arm angle, $\dot{\alpha}$ is arm angular velocity, $k_{p\propto}$ is proportional gain for arm angle, Pos is positive, Neg is Negative and Z is zero.

Above Figures 13 is concerned to Lab-view model for input membership function of Energy (E) and output proportional gain shown accordingly; fuzzy intelligence is shown in Table 2. Similarly, Figure 14 depicts inputs and output and fuzzy rules associated with it in Table 3.

The Lab-view design is executed with fuzzy and non-fuzzy to show comparison for given input parameters and outputs as shown in Figure 15 and 16. The total swing-up time is the settling time and the fuzzy controller took under half of time in conventional P controller to achieve upright. The Lab-VIEW code succession is appeared in Figure 10. The control switch is the QNET 2.0 Rotary pendulum Balance control. By analyzing figures 15 and 16, it can be stated that initially the pendulum stabilizes in 5 seconds; whereas, it took less than 2 seconds, when balance control and swing control parameters were altered.

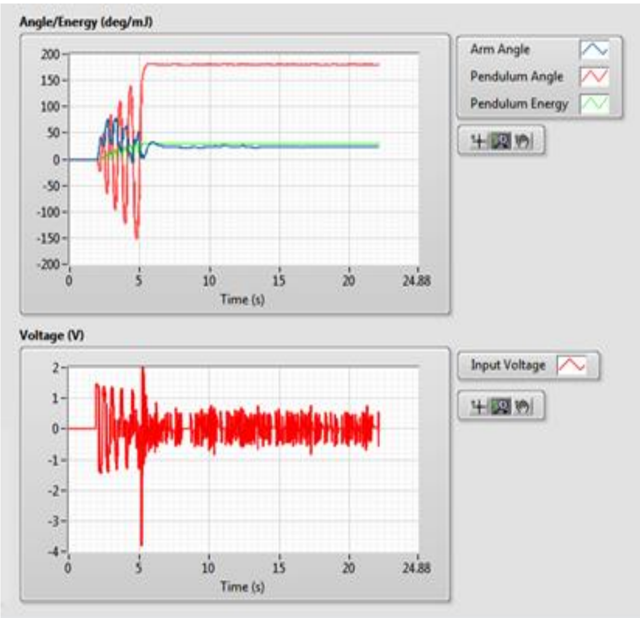

Figure.15. Model Output with PD controller.

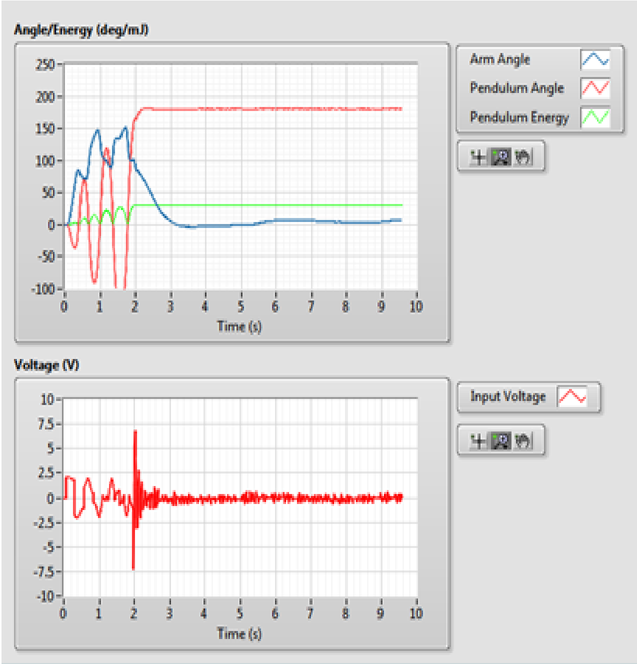

Figure.16. Model Output with PD + Fuzzy controller.

4. Conclusion

In this research, a fuzzy PD controller was designed for QNET-2.0 Rotary Inverted pendulum; however built-in PD controller was replaced. The modeling required varying values of fuzzy logic, where fuzzy controller was made with Lab-view. In last, comparative analysis was observed between Fuzzy PD controller and original PD controller. After experimental analysis of both models it was noted that fuzzy PD gave smaller steady state error and faster settling time than conventional PD controller. Furthermore, pendulum with fuzzy PD controller was susceptible to less power; it required approx. 30% power as that of PD controller. Concluding, fuzzy PD controller was successful and efficient controller designed than original PD controller.

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