Self-tuned Fuzzy-PD Control for QNET 2.0 Rotary Inverted Pendulum using lab-view

Engr. Amjad Ali, Arbab Nighat

Abstract: An Inverted pendulum is a nonlinear system and broadly utilized as automated arm. The challenge is to balance the pendulum that can rotate in only two ways, either to the positive or to the negative direction ±180 Degree. This research work is aiming to design a controller based on self-tuned fuzzy logic and (Fuzzy-PD) for QNET-2.0 Rotary Inverted Pendulum using lab-view. This self-tuned fuzzy PD control is responsible to generate computer based signals for stable outputs and can works on errors. Rotary Inverted pendulum (RIP) is used as real time model where self- tuned fuzzy PD control is applied for stabilization. There are two aspects to the control objectives for the inverted pendulum: swing-up and balance in a typical PD system, the balancing controller is generated using a fuzzy logic controller, instead of the proportional term. the swing-up controller is generated in a standard proportional controller by using a fuzzy logic system, instead of the proportional term. To build Lab-VIEW approaches, a software development technique is used to help programmers produce code that has greater potential to solve a problem as opposed to writing code without a design. This approach also helps make coding more accessible, more flexible, and more changeable. Rotary Inverted pendulum systems were operated and managed by means of the PD module and the Fuzzy PD Module in Lab-VIEW. The fuzzy controllers are added into the system after the design of the standard PD and P controllers. The two types of controllers the fuzzy P and the fuzzy P-D, and the common proportional and standard PD, are finally implemented and evaluated on the actual inverted pendulum hardware, and also the Control system output is compared between two different control methods.

Keywords: Rotary, Inverted Pendulum, Fuzzy Logic, PD control, Self-tuned Fuzzy Controller.

I. INTRODUCTION

The Rotary Inverted Pendulum basically exhibits the non-linear behavior therefore its stabilization with different control designs are complex task. Different controls are applied such the proportional, integrator, derivative (PID), Robust control and fuzzy logic design. [1] The dynamics of RIP is shown in Figure.1.
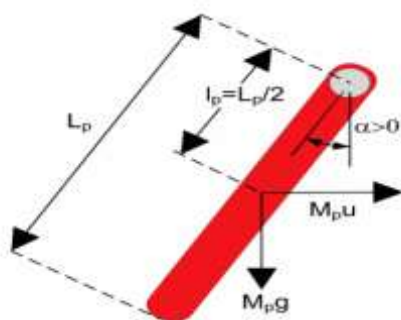

Figure 1. Free Body Diagram of Pendulum [2]

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Numerous control designs have been done by many researcher [8-10]. The inverted pendulum works on the Newton's 3rd law of motion. [9]. The main objective of this research work is to design the fuzzy based PD control for swing-up and balancing position for rotary inverted pendulum. The model contains pivoted base having the narrow steel pole of the pendulum, indicated as rotate point and it is mounted on a heading. The pendulum rotational angle " α" and arm angle " θ " moves on a level plane and has to stabilize the pendulum. To balance the pendulum in equilibrium state, a PD fuzzy controller is utilized. The zero reference point of pendulum's pole is connected to one of 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. [12]
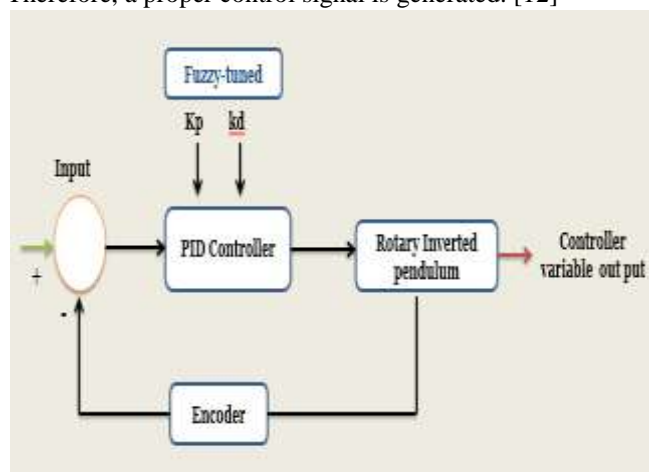

Figure 2. Proposed control block diagram.

A. LAB-VIEW

Lab-VIEW is an integral part of virtual instrumentation as it provides a developer-friendly application development environment specifically designed to support the engineers. [3] Lab-VIEW provides powerful features making it easy to connect to a wide range of hardware and other software One of the most powerful features Lab-VIEW provides the interactive programming experience to engineers and scientists through knobs, buttons, dials, and graphs. One can configure front panels to imitate conventional instrument control panels, build personalized test panels, or visually display process control and operation.

The resemblance between common flow charts and graphic systems shortens the path of learning correlated with standard languages based on text. [7]
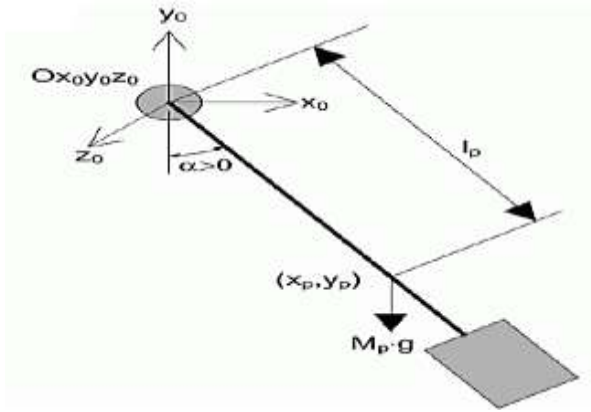
B. System Kinematics

Figure 3.Diagram of free body RIP [11]

$$x_p = l_p \sin(\alpha(t)) \qquad (1)$$

$$y_p - l_p \cos(\alpha(t)) \qquad (2)$$

In same way by derivation of differentiation, get velocities as:

$$dx_p = l_p \cos(\alpha(t))(\tfrac{d}{dt}\alpha(t) \qquad (3)$$

$$dy_{p} = l_p \sin(\alpha(t))(\tfrac{d}{dt}\alpha(t) \qquad (4)$$

C. Potential Energy: (P.E)

y_p is used to find the potential energy, Ut:

$$Ut(\alpha) = Mp\, gLp\,(1 - \cos(\alpha(t))) \quad (5)$$

Pendulum position at down word position, $\alpha = 0$,

$$U_t(\alpha = 0) = 0J$$

Pendulum is at the upright position, $\alpha = \pi$,

$$U_t(\alpha = \pi) = Mp\, g\, Lp$$

D. Kinetic Energy: (K.E)

T_t is used for pendulum rotation.

$$T_t = \tfrac{1}{2}Jp\,\alpha^2 \qquad (6)$$

Where α & is rotational velocity of inverted pendulum.

E. Pendulum Inertial Movement

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

$$T_p = 0,\ \alpha = 0 \qquad (7)$$

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

$$J_p(\ddot{\alpha})_+ M_p\, g\, L_p\,\alpha_= 0 \qquad (8)$$

Use the same initial condition

to resolve the linearized equation.

$$\alpha(0) = \alpha_0 \qquad (9)$$

$$\dot{\alpha}(0) = 0 \qquad (10)$$

then, the Laplace transform of the linearized equation:

$$J_p\,(s^2\alpha(s)-\alpha_0) + M_g g L_p\alpha(s) = 0 \quad (11)$$

$$\alpha(S) = \frac{\alpha_0\, J_p}{M_p g L_p S + J_p S^2} \qquad (12)$$

Therefore, the frequency f

$$f = 2\pi\sqrt{\frac{M_p\, g\, L_p}{J_p}} \qquad (13)$$

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

$$J_p = \frac{M_p\, g\, L_p}{4\,\pi^2\, f^2} \qquad (14)$$

While putting system parameter values of $\frac{M_p\, g\, L_p}{4\,\pi^2\, f^2}$ in equation no.14 then value of J_p should be (**0.0769 kg.m²**).

II. METHODOLOGY

Main QNET 2.0 Rotary Pendulum features:
- Compact and complete rotary servo system for NI ELVIS II (+)
- 18V direct-drive brushed DC motor
- Encoders mounted on DC motor and pendulum
- Built-in PWM amplifier
- Build-in PCI connector for NI ELVIS II (+)

Figure 4. Quanser QNET 2.0 with NI ELVIS II Board [5]

The main QNET Rotary Pendulum's parameters are shown in Table 1. The QNET Rotary Pendulum includes a direct-drive 18V brushed DC motor housed in a solid aluminum frame. The single-ended optical shaft encoders used to measure the angular position of the DC motor and pendulum of the QNET Rotary Pendulum. The complete specification sheet of the E8 P optical shaft encoder is given in E8P Data Sheet.

Table 1. Rotary Inverted Pendulum Specification.

Symbol	Description	Value
V_{nom}	VOLTAGE	18 v
R_m	TERMINAL RESISTANCE	8.4
K_t	TORQUE CONSTANT	0.043 nm/a
J_p	PENDULUM MOMENT OF INERTIA.	1.88 Kg.m2
K_m	MOTOR BACK EMF	0.043 v/(rad/s)
J_m	ROTO INERTIA	4.1×10^{-6} kgm2
L_m	ROTORINDUCTANCE	1.17 mh
M_h	MODULE ATTACHEMENT HUB MASS	0.017 kg

R_h	MODULE ATTACHEMENT HUB RADIOUS	0.0112 $_m$
Jh	MODULE ATTACHEMENT MONENT	0.7×10^{-6} kgm2
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 $_m$

The proposed fuzzy based PID control shows in Figure.5. the parameters for Rotary Inverted pendulums is designed in Lab-view and then send to the encoders to shows the position of pendulum, Arm angle, and Energy of pendulum.
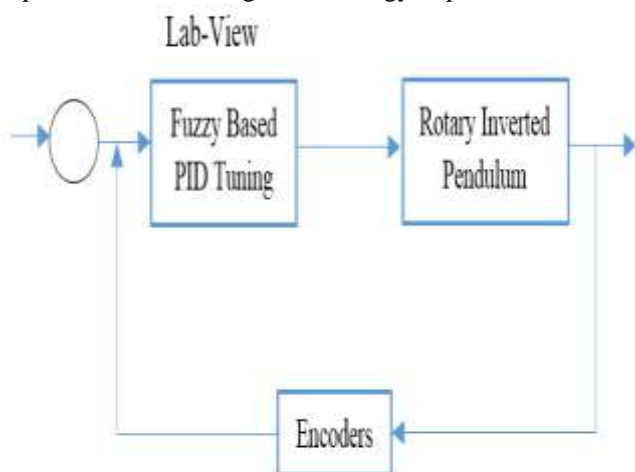
Figure 5. Block Diagram of Fuzzy Tuning of Rotary Inverted Pendulum.

The QNET Rotary Pendulum provides communication interface with the NI ELVIS II (+). The interaction between the different system components on the QNET RIP is illustrated that the NI ELVIS II (+) is interfaced to the PC or laptop via USB link with QNET Rotary Pendulum. The NI-ELVIS II (+) block reads the angular encoder inputs and commands the power amplifier that drives the DC Motor.
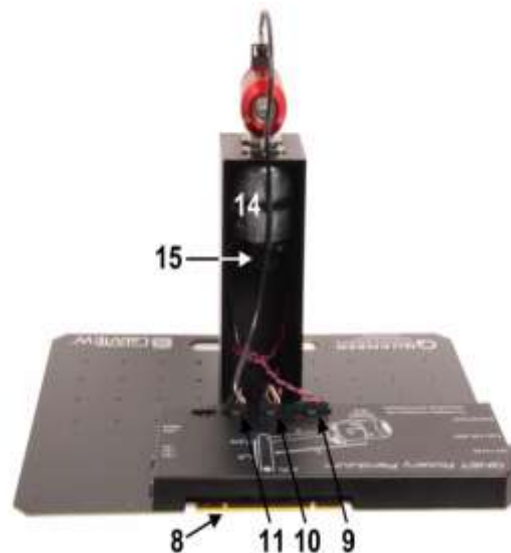

Figure 6. Front view QNET-2.0 RIP

Figure 7. Rear view QNET-2.0 RIP. [4]

The controller is designed and applied to RIP. The objective of fuzzy based tuning of PID control is to stable the RIP at up position and keep balance in upward direction. Therefore, two controls are designed; one for swing up control and another is for balance position as shown in figure-8. The swing-up controller produces the torque associated with a pendulum base arm invert the pendulum in upward direction. When a pendulum is swing-up, the balance controller expects to start its controlling for balance that position.
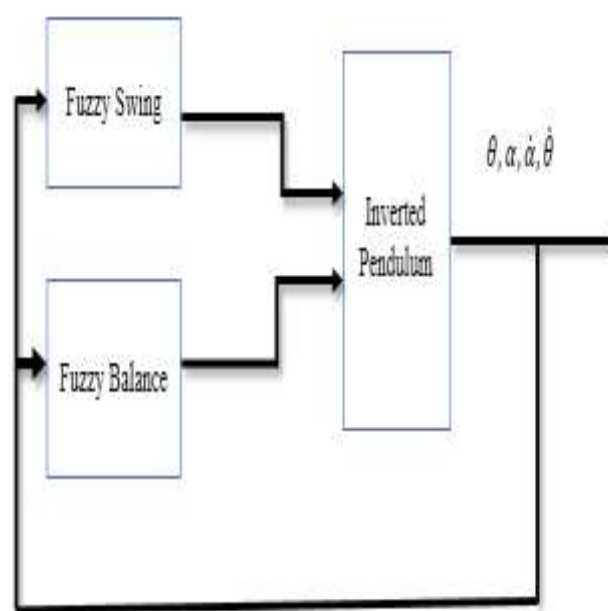

Figure 8. Block Diagram of Swing up and balance Controller

Note that in Figure.8. for fuzzy swing-up controller, energy (E) is taken as input quantity while gain (µ) is considered as output. The fuzzy P controller is to create an initial thrust when the pendulum is downwards; desired gains are achieved as output. pendulum's angle (α) and angular velocity ($\alpha\dot{}$) are the input quantities for

PD-fuzzy balance controller that gives output quantity proportional gain ($k\_(p,\alpha)$). When pendulum angle and angular velocity are negative or positive, small power is given to DC motor for balancing controller. If angle and angular velocity are reciprocals of one another like angle is negative and angular velocity is positive or the opposite, then the gain will be supplementary. The designing of fuzzy rules for Swing-up Controller are given to calculate the energy of pendulum, so the energy is constant when the arm is balanced at 30.368mj.
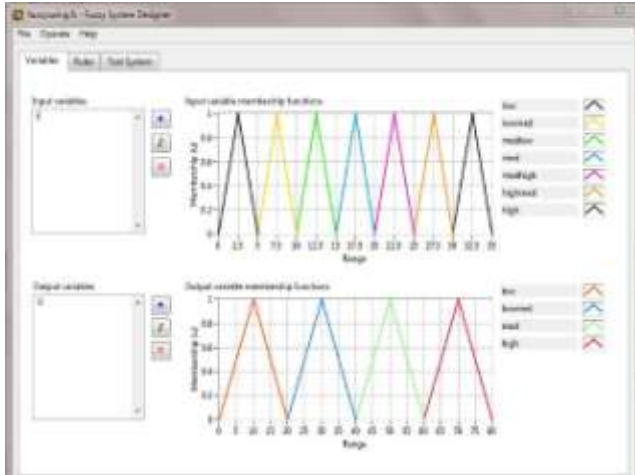

Figure 9. Input/output Membership function for Swing up Controller

Table.2. Fuzzy If- then rules of Swing-up control.

1)	IF 'Input E' IS 'LOW' THEN 'Output μ' IS 'HIGH'.
2)	IF 'Input E' IS 'LOW,MED' THEN 'Output μ' IS 'MED'.
3)	IF 'Input E' IS 'MED,LOW' THEN 'Output μ' IS 'MED'
4)	IF 'Input E' IS 'MED' THEN 'Output μ' IS 'LOW,MED'.
5)	IF 'Input E' IS 'MED,HIGH' THEN 'Output μ' IS 'LOW,MED'
6)	IF 'Input E' IS 'HIGH,MED' THEN 'Output μ' IS 'LOW,MED'
7)	IF 'Input E' IS 'HIGH' THEN 'Output μ' IS 'LOW'

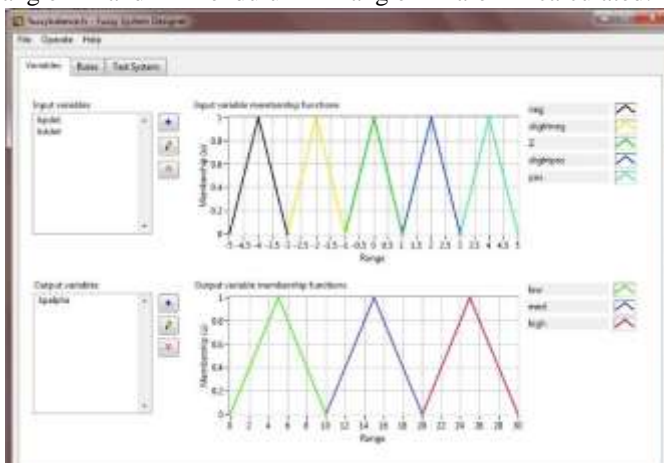Designing of Fuzzy Rules for Balance Control in which Arm angle and Pendulum angle are calculated.

Figure 10. Input/output membership functions of Balancing Control.

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

1)	If kp, dot is 'Neg' and Kd, dot is 'Neg' then $K_{p,\alpha}$ is LOW.
2)	If kp, dot is 'Neg' and Kd, dot is 'Z' then $K_{p,\alpha}$ is MID.
3)	If kp, dot is 'Neg' and Kd, dot is 'Pos' then $K_{p,\alpha}$ is HIGH
4)	If kp, dot is 'Slight Neg' and Kd, dot is 'Neg' then $K_{p,\alpha}$ is HIGH.
5)	If kp, dot is 'Slight Neg' and Kd, dot is 'Z' then $K_{p,\alpha}$ is HIGH
6)	If kp, dot is 'Slight Neg' and Kd, dot is 'Pos' then $K_{p,\alpha}$ is HIGH.
7)	If kp, dot is 'Z' and Kd, dot is 'Neg' then $K_{p,\alpha}$ is HIGH
8)	If kp, dot is 'Z' and Kd, dot is 'Z' then $K_{p,\alpha}$ is HIGH.
9)	If kp, dot is 'Z' and Kd, dot is 'Pos' then $K_{p,\alpha}$ is HIGH
10)	If kp, dot is 'Slight Pos' and Kd, dot is 'Neg' then $K_{p,\alpha}$ is HIGH.
11)	If kp, dot is 'Slight Pos' and Kd, dot is 'Z' then $K_{p,\alpha}$ is HIGH.
12)	If kp, dot is 'Slight pos' and Kd, dot is 'Pos' then $K_{p,\alpha}$ is HIGH.
13)	If kp, dot is 'Pos' and Kd, dot is 'Neg' then $K_{p,\alpha}$ is HIGH
14)	If kp, dot is 'Pos' and Kd, dot is 'Z' then $K_{p,\alpha}$ is MID.
15)	If kp, dot is 'Pos' and Kd, dot is 'Pos' then $K_{p,\alpha}$ is LOW.

Figure.9 Shows Input/output Membership function for Swing up Controller and Fuzzy If- then rule for Swing-up controller is shown in Table-2. Similarly, Figure.10 is showed Input/output Membership function for balance control and fuzzy If-then rule for Balancing Control are showing in Table 3.

III. RESULT AND DISCUSSION

The execution of control strategy that has been discussed in this research work obviously involves hardware components. The main components comprising the QNET Rotary Pendulum are labeled in Figure 6, and Figure 7. System states $\alpha, \dot{\alpha}, \theta, \dot{\theta}$ are responsible to read data from sensors, after hardware is all set and compatibility interface is built between NI Lab-view. These states are then feed to control switch for determining which controller is needed whether balance or swing, in result equilibrium is achieved shows in Figure 11. the Lab-View Controller where reading sensor data and measuring quantities arm angle (θ in radians) and link angle (α in radians). In addition, Figure 12 and 13 signify Lab-View sub-system of Swing controller and balancing controller.

Figure 11. Physical model of Rotary Inverted Pendulum at swing-up and balance position.

The different blocks in Lab-view is showing in Figure-12. Similarly, in Figure-13, different blocks related to balancing controller is shown.
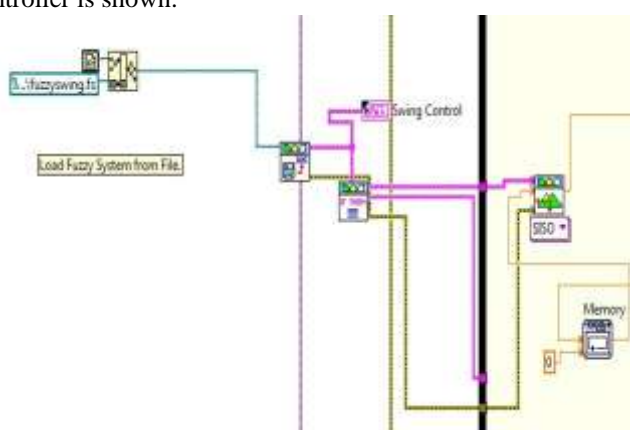

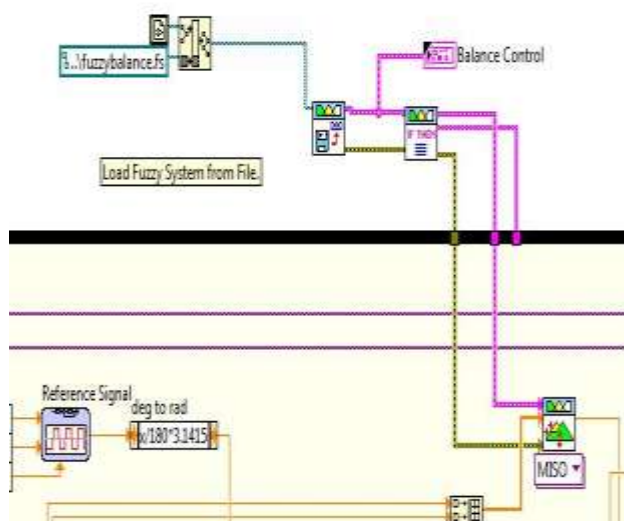**Figure 12. Blocks related to swing- up control in Lab-View.**

Figure 13. Blocks related to Balance Control in Lab-view.

The values processed by control switch to decide which controller should trigger for proper stabilizing rotary inverted pendulum. Swing control calculates the energy, then it is taken to the next step where linear acceleration is appropriately estimated so that the pendulum comes s in upright position having voltage output for DC motor.
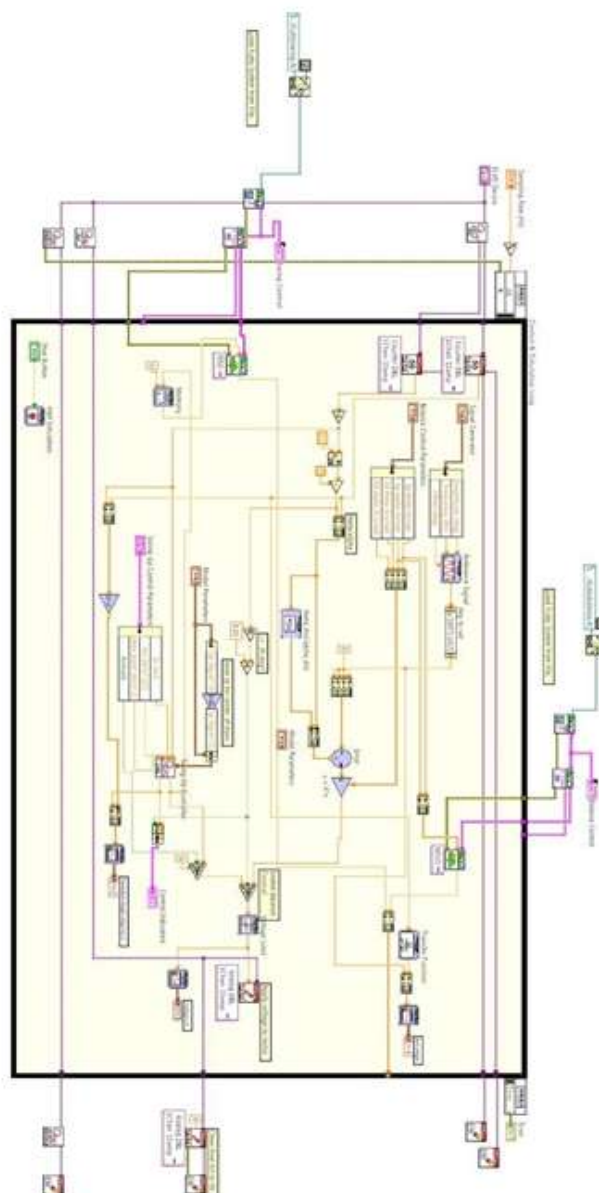

Figure 14. Fuzzy PD Controller in Lab-view

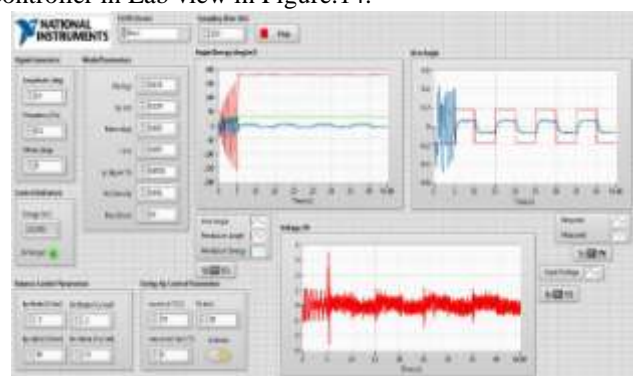The proposed fuzzy-PD control is compared with existing PD Controller in Lab view in Figure.14.

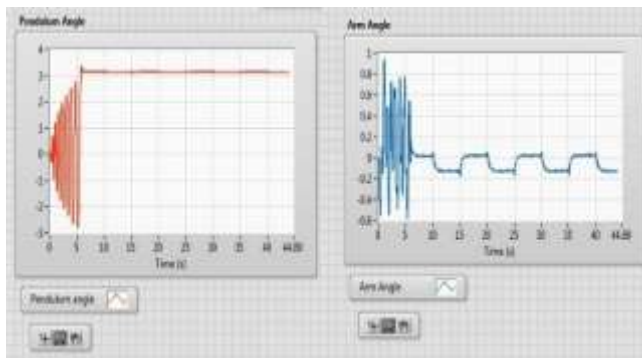**Figure 15. Front panel using existing PD Controller**

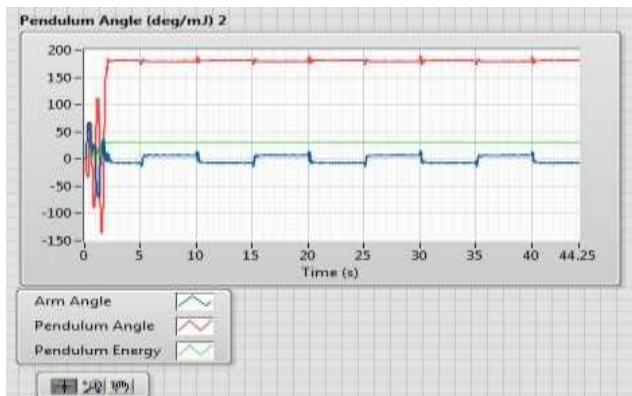**Figure 16. Pendulum Angle and Arm Angle in Existing PD Controller**

Figure 17. Pendulum Angle (red), Arm angle (blue) and Energy (green) using Fuzzy tuned PD Controller
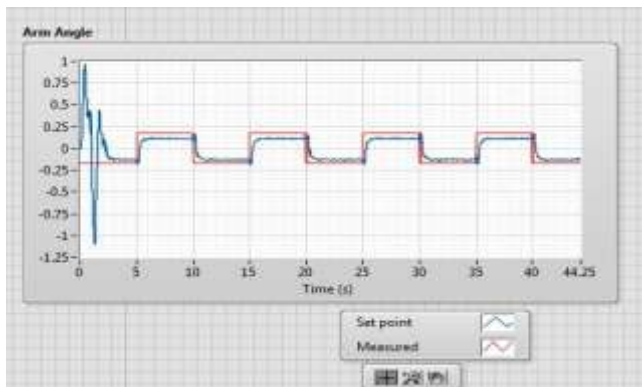

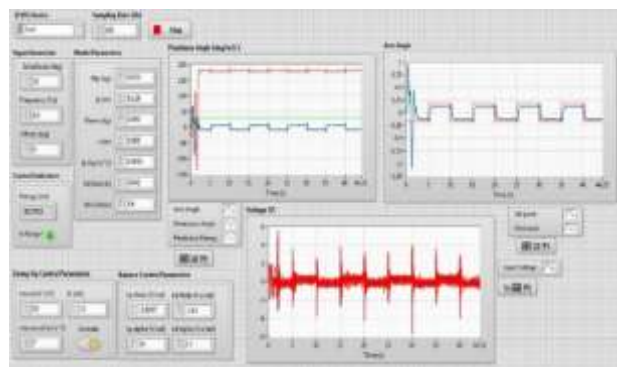**Figure 18. Arm angle and Set point using Fuzzy tuned PD Controller**

Figure 19. Fuzzy Tuned PD control Front panel

After analyzing the results, it can be stated that initially the pendulum takes more time for Stabilization; whereas, it took less time Stabilization. The Comparison of the two controls is shown in Table 4.

Table.4. Comparison of Existing PD and Tuned Fuzzy PD Controller.

Controller	Total Swing up time	Arm Amplitude	Pendulum Energy	Arm Angle during Max. Swing	Voltage during Transient position	Voltage After Stable Position	Pendulum Angle (Inverted)
Existing PD	5 Sec	10°	30.370	-0.4 to 0.4	-2.5 to 3.5	-0.75 to 0.75	180°
Fuzzy Tuned PD	2 sec	10°	30.370	-1 to 1	-3.5 to 5.5	-0.5 to 0.5	180°

IV. CONCLUSION

The aim of this research is to allow use of the Fuzzy Logic Control based controller to develop the inverted pendulum device control algorithm. All the mechanisms and ideas behind this type of controller were well known. Two fuzzy based PD control techniques are proposed and simulated for QNET-2.0 Rotary Inverted pendulum. These controllers are implemented in Lab-VIEW. The fuzzy logic controller was designed using Fuzzy System Designer from Lab-VIEW. The Fuzzy Logic Control + rule-based controller was selected as the alternate system that can be used to modify the PID controller, as it is interface with hardware and on-line control for efficient system. Lastly, a comparative analysis took place to compare the Fuzzy-PD controller and existing PD controller. After experiments and comparisons of both, it is concluded that, fuzzy-PD gave smaller steady state error and faster settling time than conventional PD controller. Fuzzy PD controller takes less time for Balancing so the concluding with the result that fuzzy- PD controller was more efficient and successful controller than existing PD controller. While conclusion the results, the PD controller balance the pendulum in five seconds, while Fuzzy PD Controller took two seconds to balance the QNET 2.0 Rotary Inverted Pendulum.

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