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ANFIS PD Plus I Control On Simscape Model of Nonlinear Physical System

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Abstract: Nonlinear Physical Systems involve hybrid technologies from various fields like mechatronics, embedded systems, control engineering and computing to compete with real world. The physical system taken into consideration is wheeled inverted pendulum system, which is non-linear and unhinged in nature. The paper depicts the nonlinear model in Simscape to examine the real behaviour of the Physical System and control through conventional controllers. The main goal is to control the cart's desired position and stabilize the pendulum twisted in the upright position. An analysis is carried out to attain the stable inverted location with a standard feedback controller (PID), full state feedback Linear Quadratic Regulator (LQR), 2-PID controller method and ANFIS Controller. According to the simulation results, comparisons are made among the controllers. These explorations lead to understand the control aspects of Nonlinear Physical System.

Keywords: Nonlinear Physical System, Wheeled Inverted pendulum, PID, LQR, 2-PID, ANFIS PD plus I

1. INTRODUCTION

A Nonlinear Physical System is mechanically designed and configured with artificial intelligence to do their assigned task autonomously. Wheeled inverted pendulum is highly unstable, nonlinear and belongs to the class of standard benchmark complex system in control engineering (Kim and Kwon, 2017). The inverted pendulum problem or an inverted pendulum on the cart must be solved in order to make a self-balancing robot (Mahmoud et al., 2013). It is a nonlinear understated non-minimum step process that applies the three degrees of freedom movement including pitch, yaw and straight motion (Li and Yang, 2012). It is very difficult to control than other benchmarking devices such as the Cruise Control System ball and beam, etc.

The Linear Quadratic Regulator guarantees stability and act as a robust controller in selecting the optimal weighting matrices Q and R, which is key to receiving feedback (Nath and Dewan, 2017). An attempt was made to pick the weighting matrices by means of a few smart optimization techniques and applied to a nonlinear unstable rotary inverted pendulum to check the output. In (Bakarac et al., 2018), the mathematical modelling and three controllers like PID, LQR and Model predictive Control (MPC) are involved in analyzing the inverted pendulum system to maintain the vertical position. Since the dynamics of inverted pendulum are very simple, to develop an explicit MPC in the form of a piece-by-piece affine function to allow the optimal control law to be estimated quickly.

The recurrent neural network and proportional-integral derivative (PID) are combined to form a nonlinear adaptive neural network controller for unknown single-input / multi-output multivariable system (Cong and Liang, 2009). Such a unique formation makes the neural network controller's exterior function capable of becoming a P, PI, PD or PID controller while required. The projected controller will change the neural network's online based on errors occurred by unpredictable process variables such as modeling error and external interference hinged on steady learning levels. Instead of the gradient, the robust back-propagation algorithm is used to change the network weights.

An attempt to control an inverted pendulum by using ANFIS that climbs up an inclined plane (Kharola and Patil, 2017). A Proportional-Integral-Derivative (PID) controller is designed to control Offline Inverted Pendulum on Inclined Aircraft (IPIP). The PID controller generated data sets were also used to train an ANFIS system. Neuro-fuzzy systems are a mishmash of Neural Network and fuzzy sets and give a powerful device to model system behaviour (Collotta et al., 2014). The NN is used to term the clustering in the solution space that results the formation of fuzzy sets (Kusiak et al., 2014). Adaptive Neuro-Fuzzy Inference System (ANFIS) (Chan et al., 2012) belongs to a class of adaptive networks incorporating the learning features of Neural Networks (NNs) and the language implementations of Fuzzy Logic Systems. In soft computing, ANFIS is a successful process for predicting presentation. A statistical study and soft computing system hinged on the ANFIS Neuro-fuzzy proportional-integral-differential (ANFP) control is planned to forecast the concert of a fuzzy PID controller for a two-axis inertial stable platform scheme (Liu et al., 2014). The model is trained using the learning algorithm Levenberg-Marquardt (LM) and measured according to experimental data from the ANFP controller's performance results. In (Prabhakar et al., 2018), the Fuzzy Proportional- Derivative Controller (PD) plus I is designed for a nonlinear cruise control system to provide adaptive performance in set-point tracking. This demonstrates the layout of the fuzzy PD plus I controller and contrasts both simulation and and real-time with control structures such as PID, I –PD and PI-D.

(Marikkannan et al., 2019) Adaptive neuro-fuzzy inference system (ANFIS) regulator for zero voltage switching (ZVS) asymmetrical pulse width modulated (APWM) full-bridge converter with high voltage gain is planned for power harvesting purpose. Converter has specified constant input current, little switching losses, advanced efficiency and superior power density as a result of zero voltage switching. ANFIS controller has offered better organize to uphold stable converter output voltage for any one of power harvesting purpose. ANFIS controller illustrates proportional integral, fuzzy logic and fuzzy proportional, integral and derivative controllers.

(Omer Saleem Bhatti, 2018) The PID organizer progress the transient response and strongly nullifies the things of exogenous turbulence. The concluding organize result is subscribed as the weighted amount of individual production from the ANFIS and PID controller. A hyperbolic tangent function (HTF) of the fault vibrant is used to discrepant the weights adaptively in the organizer grouping. This quality vigorously vary the assistance of individual organize attempt, offered by ANFIS and PID controller, with reference to the difference in the angular-error dynamic. The PID constraint and the variation-rate of HTF are meta-heuristically adjusted via an adaptive particle swarm optimization (APSO) process.

(Gansari and Buiu, 2017) Swarm robotics has increased drive in the previous years owing to impressive technical and scientific progress. A broad variety of purpose area profit from the power of group performance and developing intellect even if the individual representative in a swarm is easy and have partial sensing and giving out capability.

In common, fuzzy controller has two inputs “error” and “change in error”. Fundamentally there are two kinds in two-input fuzzy organizer. The primary one is a PD-type fuzzy organizer, which produces control indicator as of “error” and “change in error” as well as called as the position type organizer. The former one is PI-type fuzzy organizer. It employs a alike information issues as the PD-type fuzzy organizer but has incremental organize reaction, and also called as the velocity-type organizer. But the PD-type organizer without help cannot remove the steady-state error. And PI-type only has restraint in getting better transient response. It is further random to construct the PID organizer using one-output fuzzy system and three-input and in addition very hard to shape the fuzzy control system impulsively.(Edgar and Victor, 2006) To beat these problem, the fuzzy PID organizer that use multiple “two-input fuzzy organizer” or partly fuzzy modified linear PID organizer are rising. The direct relationship of the presentation between the fuzzy PID and linear PID is extremely hard. However, because lots of scheme on how to tune a conventional organizer have been projected, the tuned PID factors can be used as the basis of pick fuzzy PID organizer using the connection between a fuzzy PID organizer and its equivalent PID controller.

The goal of the work is to design and analyze the control features involved in Simscape model of the nonlinear unstable robotic system. The wheeled inverted pendulum parameters such as pendulum angle and cart position are regulated by traditional controllers and ANFIS PD plus I Controller. The conventional controllers like PID, LQR and double PID is compared with the ANFIS PD plus I controller based on the performance characteristics like angle deviation and cart position. The purpose of Simscape software is to create models for physical systems based on environmental constraints. Simscape additional products afford extra difficult mechanism and analysis abilities. It is very helpful to develop and test the control systems.

2. SYSTEM MODELLING

2.1 Requirement Analysis

The four-wheeled inverted pendulum system is previously a unique illustration that is usually established in the reference system control and study literature. That theory is partially based on the reality that it is not controllable for all machine parameter values, i.e. the pendulum actually cannot balance itself upright.

The process equations dynamics are nonlinear. The key basics of the control system are to stabilize the inverted pendulum with a force applied to the character point. The Wheeled Inverted Pendulum or Segway device is a real-world example directly related to the inverted pendulum scheme.

In the later case, two-dimensional difficulties were considered where the pendulum is forced to move vertically. The control input for this device was the force F that pushes the cart straight and the outputs are the an gular arrangement of the pendulum at a distance of x from the origin. By taking this example, take a device that contains all the experimental components with all these features. The free body diagram of wheeled inverted pendulum is shown in Figure 1.

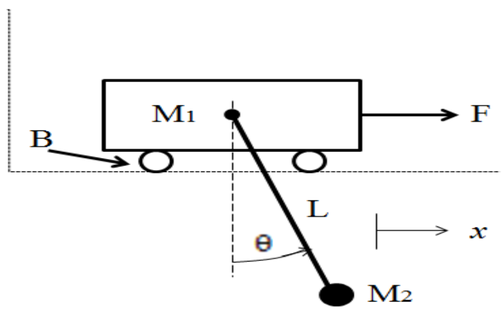


Fig. 1. Wheeled inverted pendulum System Equations.

By referring several literatures (Agarana, 2017; Pousti, 2008), dynamics of the wheeled inverted pendulum are indicated in the formation of following two equations,

$$(M_1 + M_2)\ddot{x} + B\dot{x} + M_2L\ddot{\theta}\cos\theta - M_2L\dot{\theta}^2\sin\theta = F \quad (1)$$

$$(I + M_2L^2)\ddot{\theta} + M_2gL\sin\theta = -M_2L\ddot{x}\cos\theta \quad (2)$$

Table 1. System Specifications.

Parameters	Quantity
Mass of Cart (M_1)	0.5 Kg
Mass of Pendulum (M_2)	0.2 Kg
Length of Pendulum from the hinge point (L)	0.3 m
Coefficient of frictional Force (B)	0.1Ns/m
Gravity (g)	9.8m/s^2
Moment of Inertia of the Pendulum (I)	0.006 Kgm^2
Force to the Cart (F)	1 N

2.2 Nonlinear Simscape Model

We alternatively show how to build the inverted pendulum model using the physical modeling blocks of the Simscape extension to Simulink. The blocks in the Simscape library represent actual physical components. Therefore the complex multi body dynamic models can be built without mathematical equations from physical principles which were done by applying Newton's laws to generate the model implemented in Wheeled Inverted Pendulum.

Figure 2 shows the simscape prototype of the wheeled inverte d pendulum. The response of the simulink model is unsatisfactory based on the figure 3.

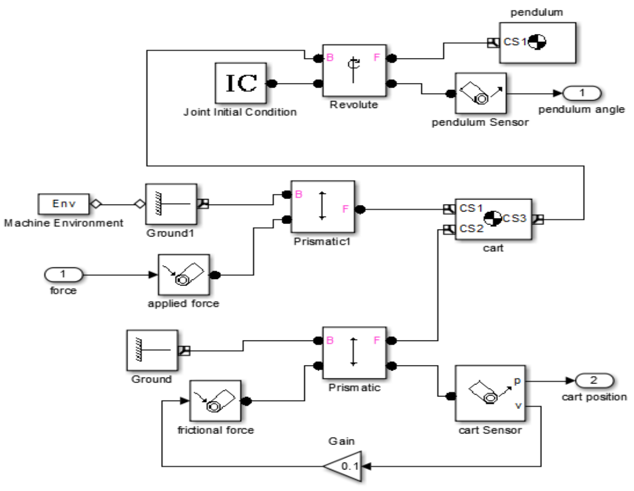
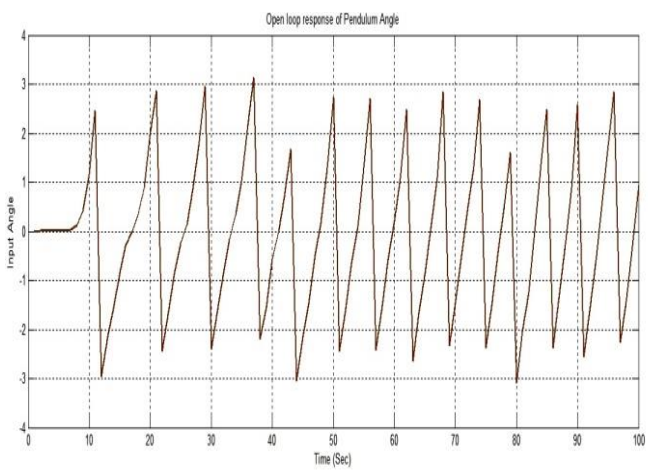
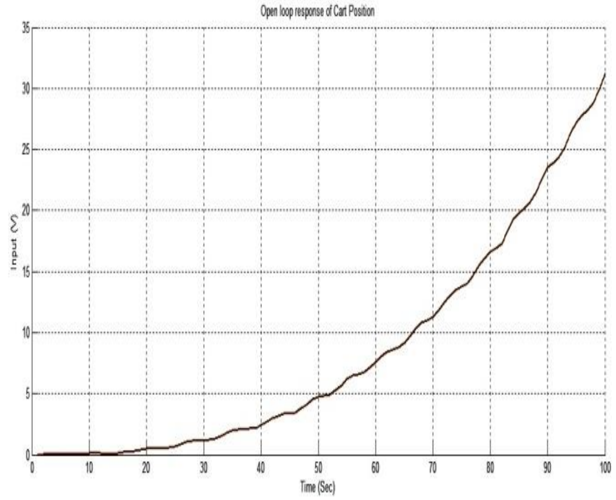


Fig. 2. Simscape Model of wheeled inverted pendulum.



(a)



(b)

Fig. 3. Open Loop response a) Pendulum Angle b) Cart Position.

The angle of the pendulum is deviated more, because it should be less than 0.35 rad and the cart location goes to the right infinitely. Therefore, the system is unstable in an open loop condition when there is a small impulsive force imposed to the cart.

2.3 Sensitivity Analysis

Variance based sensitivity analysis was fulfilled by using wheeled inverted pendulum system (Prabhakar Gunasekaran et al., 2019) to create an efficient investigation of the inputs' domain. Taking the model in the form

$$Z = f(k_1, k_2, \dots, k_r) \tag{3}$$

being Z its output and ki (i:1, …, p) the model's input. With our model Monte Carlo experiment is performed. First, this requires sampling N combinations of the r inputs from their distributions of probability to achieve the following matrix

$$M = \begin{bmatrix} k_1^{(1)} & k_2^{(1)} & \dots & k_p^{(1)} \\ k_1^{(2)} & k_2^{(2)} & \dots & k_p^{(2)} \\ \dots & \dots & \dots & \dots \\ k_1^{(N)} & k_2^{(N)} & \dots & k_p^{(N)} \end{bmatrix} \tag{4}$$

Then, by evaluating the model on each combination of the p inputs, namely on each row of the matrix M, the vector of model outputs z is obtained.

$$z = \begin{bmatrix} z^{(1)} \\ z^{(2)} \\ \dots \\ z_1^{(N)} \end{bmatrix} \tag{5}$$

In order to understand how much the correct description of an input will minimise the overall uncertainty in the results, the first order sensitivity index is a very important test. It is likely to describe a model as additive if,

$$\sum_{i=1}^{p} \mathrm{S_i} = 1 \tag{6}$$

Indeed, in this case, the model's unconditional variance can be broken down into the sum of the first order effect of each single variable. In this case, a low first-order sensitivity index does not essentially suggest that the corresponding variable has a limited impact on the variance of the output, as it could contribute to it through its interactions with the other variables. A synthetic indicator to be tied with the first-order sensitivity index is the whole effects index to consider the effect of the interactions, defined as follows.

$$S_{T_i} = 1 - \frac{V_{k_{\sim i}}\left(E_{k_i}(z|k_{\sim i})\right)}{V(z)} \quad (7)$$

Input factor i's total effects index gives the number of all interaction effects involving the ith factor. When the total index is $S_{T}i = 0$, the ith factor can be unchanging without disturbing the outputs' variance. The method adopted here is illustrated as: 1) Sampling two (N, p) matrices of quasi-random numbers in the array between 0 and 1 and then the values of two matrices A and B are created using the distributions of the p input factors 2) a set of p matrices, C, is attained by gathering p matrices equal to A, except for the ith column, which is hired from B 3) This form is evaluated for all the [N(p+2)] combinations of source variables.

$$A = \begin{bmatrix} k_1^{(1)} & k_2^{(1)} & \dots & k_p^{(1)} \\ k_1^{(2)} & k_2^{(2)} & \dots & k_p^{(2)} \\ \dots & \dots & \dots & \dots \\ k_1^{(N)} & k_2^{(N)} & \dots & k_p^{(N)} \end{bmatrix} \quad (8)$$

$$B = \begin{bmatrix} k_{p+1}^{(1)} & k_{p+2}^{(1)} & \dots & k_{2p}^{(1)} \\ k_{P+1}^{(2)} & k_{P+2}^{(2)} & \dots & k_{2p}^{(2)} \\ \dots & \dots & \dots & \dots \\ k_{P+1}^{(N)} & k_{p+2}^{(N)} & \dots & k_{2p}^{(N)} \end{bmatrix} \quad (9)$$

$$C_i = \begin{bmatrix} k_1^{(1)} & k_2^{(1)} & \dots & k_{p+i}^{(1)} & \dots & k_p^{(1)} \\ k_1^{(2)} & k_2^{(2)} & \dots & k_{p+i}^{(2)} & \dots & k_p^{(2)} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ k_1^{(N)} & k_2^{(N)} & \dots & k_{p+i}^{(N)} & \dots & k_p^{(N)} \end{bmatrix} \quad (10)$$

for i=1....p

Global sensitivity analysis of wheeled inverted pendulum system is applied in Simulink using variance-based Sensitivity Method with combinations of factors produced by Monte Carlo Method with a consistent probability distribution function.

In this case, Double loop Monte Carlo method and Saltelli's single loop techniques are considered. The first order sobol index and total effect sobol index are calculated through using (7) and (8) hinged on the wheeled inverted pendulum system evaluations y_{A}=*f(A)*, y_{B}=*f(B)* and y_{C}=*f(C)* for double loop Monte Carlo Simulation (MCS) scheme and single loop Saltelli simulation scheme. The double loop technique leads to an emergence of transformation from N x D input matrix to Nx1 outputs, where N represents the quantity of samples and D represents the Dimension of Input. The advantages of a double-loop MCS scheme are high precision and simple programming. The computational cost function for double loop is $n^2D + n$. Then to lower the computational cost, a single loop technique (2n+nk) is used.

Table 2. Input factor spans for Wheeled Inverted Pendulum.

Variables	Values	
	Lower Bound	Upper Bound
Mass of Cart (M_1)	0.2 Kg	1.0Kg
Mass of Pendulum (M_2)	0.1 Kg	1.0Kg
Length of Pendulum from the hinge point (L)	0.1 m	0.7 m
Coefficient of frictional Force (B)	0.05 Ns/m	0.5 Ns/m
Moment of Inertia of the Pendulum (I)	0.002 Kgm^2	0.010 Kgm^2
Force to the Cart (F)	0.5 N	2 N

The input variables are Mass of Cart (M_1), Mass of Pendulum (M_2), Length of Pendulum from the hinge point (L), Coefficient of frictional Force (B), Moment of Inertia of the Pendulum (I) and Force to the Cart (F).

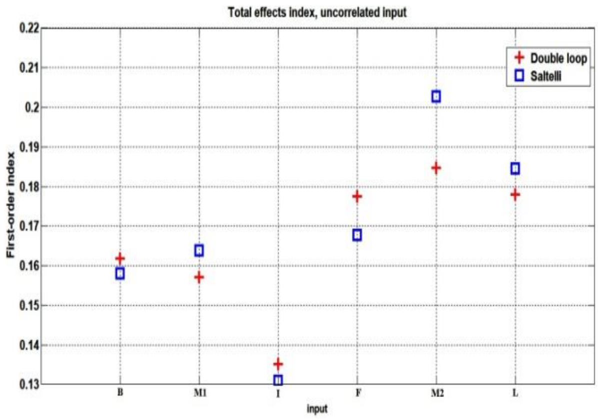


Fig. 4. Total Effects Index, uncorrelated input.

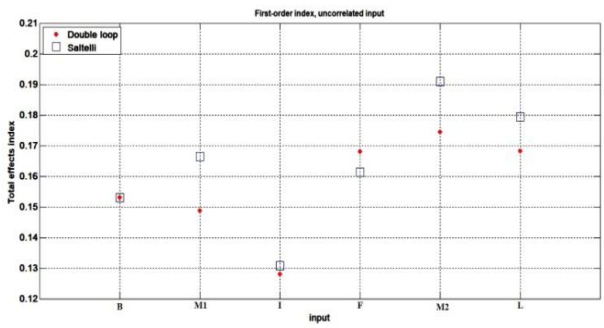


Fig. 5. First Order Index, uncorrelated input.

These input variables are considered as uncertain. Table 2 represents the Input factor spans for Wheeled Inverted Pendulum. First order and total sensitivity indices for the Wheeled Inverted Pendulum based on cart position and pendulum angle is shown in Figure 4 and 5. The Mass of Pendulum (M_2), Length of Pendulum from the hinge point (L) and Input Force to the Cart (F) are the three input factors that influence the behaviour of Wheeled Inverted Pendulum in an extreme manner. The other factors do not show much control on the response hinged on this Global sensitivity analysis technique.

3. DESIGN OF PID CONTROLLER

Proportional-Integral-Derivative controller is a feedback controller whose response is typically based on the error (e) computation between a user-defined set point (SP) and an evaluated process variable (PV). Each PID controller component refers to a specific action taken on the error.

The PID controller configuration used here is an Ideal PID control with filter derivative:

$$G_c(s) = k_p\left[1 + K_i\frac{1}{s} + k_d\frac{N}{1+N\frac{1}{s}}\right] \tag{11}$$

Both the nonlinear equations are classified as fourth order non minimum phase system. After re-examining several literatures like (Dwyer et al., 2000; Prabhakar et al, 2014; Omer Saleem Bhatti et al., 2018), numerous tuning rules have been tried, but none of them is appropriate for the fourth order non minimum phase scheme. Zeigler Nichols closed loop tuning is not recommended, because the essential condition for the Routh Hurwitz stability criterion is not fulfilled. The gain values are refrained by built-in interactive PID tuned coding in Simulink. This type of tuning algorithm prefers a crossover frequency dependent on the structure of the two wheel inverted pendulum and designs a 60 degree target step span. The obtained PID gains are used in the Simulink model, which is shown in Figure 6. The retort curves for cart's location and pendulum's position are shown in Figure 7.

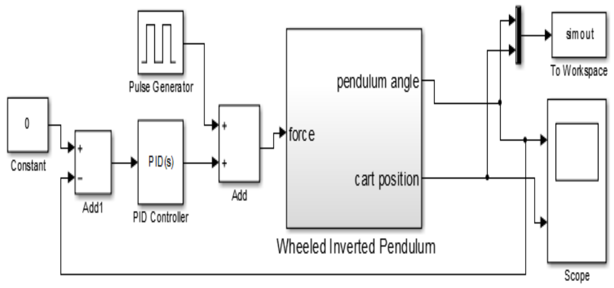
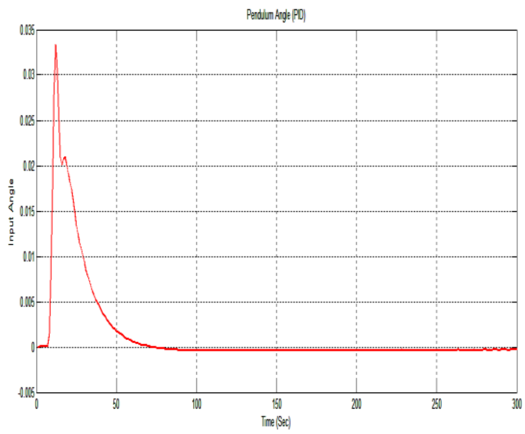
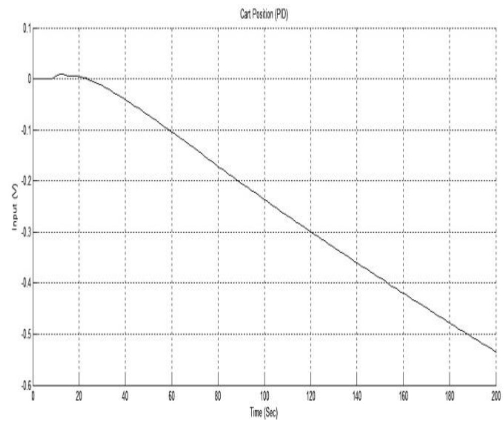


Fig. 6. Simulink model of PID Controller.



(a)



(b)

Fig. 7. Response of PID Controller a) Pendulum Angle b) Cart Position.

The PID controller can able to handle the nonlinear structure very well, because the variation of the angle from the functioning point is very small (approximately .03 radians). But the location of the cart doesn't reach its precise position, while it goes on negative path. The single PID system is not used to organize the location of cart.

4. DESIGN OF LQR CONTROLLER

LQR is a tool used in modern control theory to evaluate such a complex using state-space approach. It deals the multi-output process easily based on full state feedback (Nath and Dewan, 2017).

The LQR task in MATLAB m-file can be applied in the design of the LQR controller to determine the value of vector K that determines the feedback control law. This is completed by choosing two bounded values, input *(R)=1* and *Q=C'xC* where *C* is from state equation *Y=Cx*, involving States = $\{x, \dot{x}, \theta, \dot{\theta}\}$, Inputs = {r} and Outputs = $\{x, \theta\}$. The term r represents the reference input of the system, x represents the cart position and θ represents the pendulum angle.

The controller can be tuned by varying the nonzero *x* and *y* elements in Q matrix which is done in m-file code. Thus, by tuning the values of *x* =5000 and y =100, the subsequent values of matrix *K* are obtained as [-61.99 -33.50 95.06 18.83].

In order to decrease the steady state error of the structure output, a value of stable gain, *Nbar* should be added after the reference. Feedback is given by all states with a full-state feedback controller. The status value of the states should be determined, multiply that by the selected benefit K, and use a new value as a reference to calculate the input. Use the user-defined function that can be used in m-file code to find Nbar. The value of constant gain, *Nbar* are found to be:

Nbar = -61.9933

For a trial basis

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \text{ and } R = 1 \tag{12}$$

The simulink model of LQR controller is shown in figure 6. The response curves based on the feedback gains are shown in Figure 7.

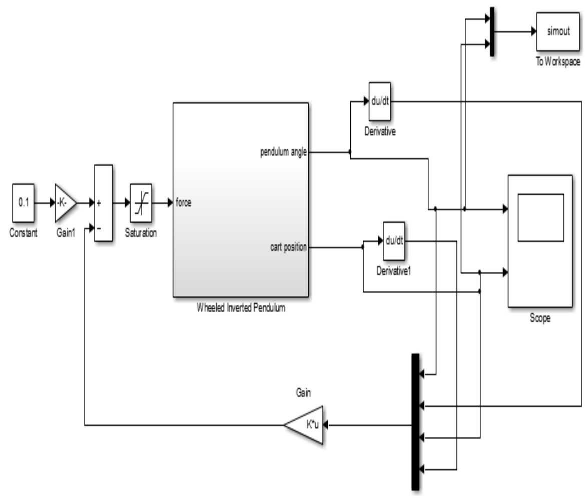
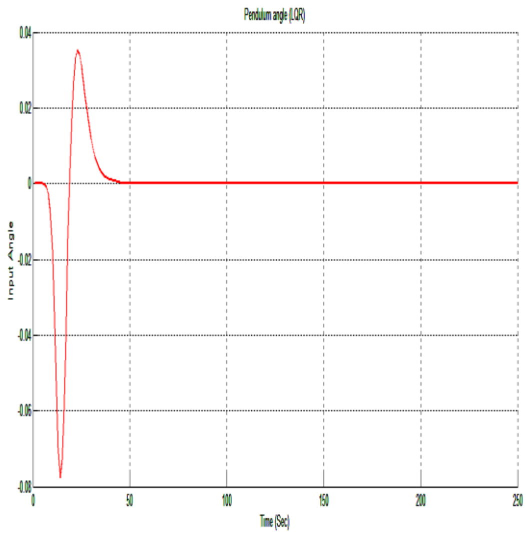
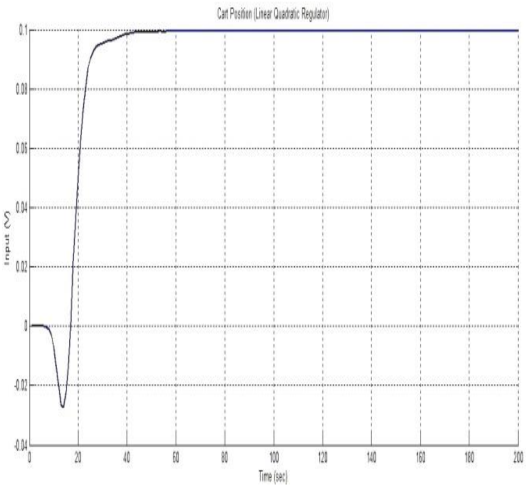


Fig. 8. Simulink model of LQR Controller.



(a)



(b)

Fig. 9. Response of LQR Controller a) Pendulum Angle b) Cart Position.

5. DESIGN OF DOUBLE PID CONTROLLER

The scheme consists of two PID controllers. ‘PID Controller 1’ controls the Pendulum’s angle and ‘PID Controller 2’ controls the cart’s location.

The PID controller structure used here is an Ideal PID controller with filter derivative:

$$G_c(s) = k_p\left[1 + K_i\frac{1}{s} + k_d\frac{N}{1+N\frac{1}{s}}\right] \tag{13}$$

The yield of the regulators are summed collectively and provided as a controlled input signal to the inverted pendulum system.

By computation of mutation, crossover and selection, Genetic Algorithm produces the initial population of the PID control factors erratically, thus improving the control parameters. Genetic simulation programming is a feasible one that searches the dissimilar compositions of existing tasks and terminals under the way of a fitness measure. IAE fitness task is applied to execute the GA for obtaining the PID controller parameters to balance the delay in this structure. The aim is hinged on IAE (IAE integrates the absolute error over time) defined as

$$objective\ function = \int_0^{\infty}|e(t)|dt \tag{14}$$

The GA tuned gain parameter values of PID controller 1 are K_P = 257.1, K_i = 229.6, K_d = 26.6 and the values of PID controller 2 are K_P = -27.2 K_i = -0.34, and K_d = - 29.3. The GA programming factors are listed in Table 3.

Table 3. Genetic Algorithm programming factors.

Variables	Value/Technique
Population Size	200
Variable Bounds	[−100,1000;-100,1000;−100,1000]
Maximum number of generations	320
Fitness functions	IAE
Selection Method	Normalised geometric selection
Crossover method	arithmetic crossover
Mutation method	uniform mutation

These detected gain variables are used in the Simulink model, which is shown in figure 10. The response curves for cart’s location, pendulum position are shown in figure 11.

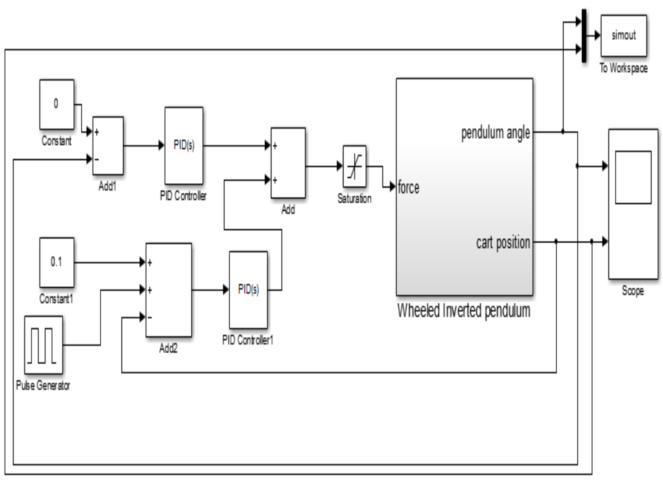
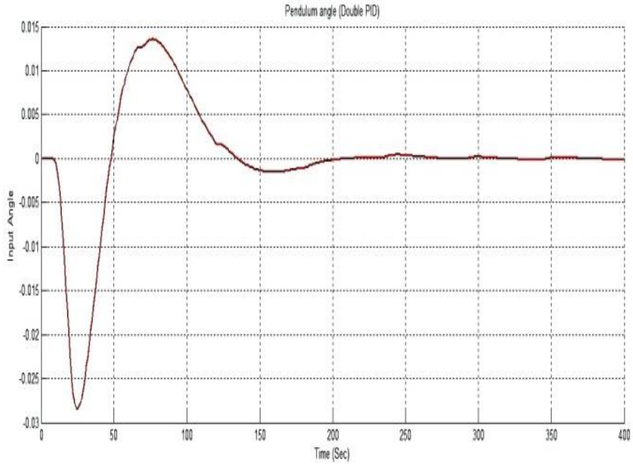
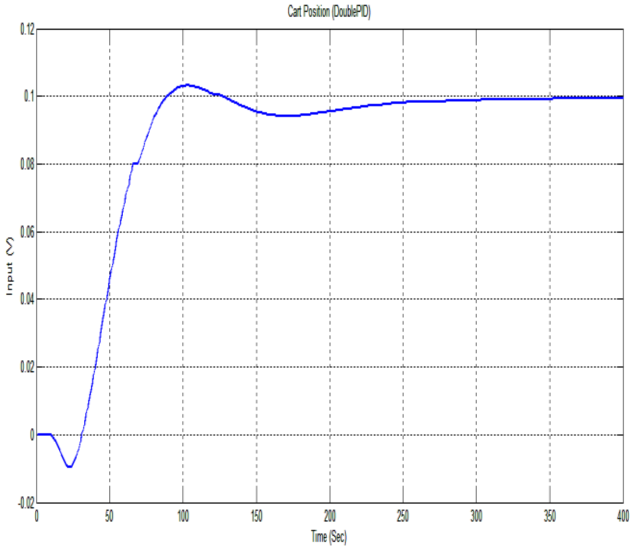


Fig. 10. Simulink model of Double PID Controller.



(a)



(b)

Fig. 11. Response of Double PID Controller a) Pendulum Angle b) Cart Position.

6. ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM CONTROLLER FOR SIMSCAPE MODEL

ANFIS are artificial neural network based on Takagi-Sugeno fuzzy inference structure, which combines the quality of both FLC and Neural networks. ANFIS is a Sugeno-type fuzzy inference scheme in which the parameters connected with particular membership functions are computed by means of either a back propagation gradient descent algorithm alone or in grouping with a least squares technique. It has been broadly applied to unsystematic data sequences with extremely irregular dynamics. Two ANFIS PD plus I controllers are designed to control the pendulum position and cart location by applying a step input as a force. The Simulink model of ANFIS PD+I Controller is shown in Figure 12. The ANFIS parameters are listed in Table 4 to perform the simulation. The comparative result analysis is shown in Table 5 based on the time domain specifications. The figures 13-16 represents the ANFIS loading data, trained data, ANFIS structure and controlled response associated to Pendulum position correspondingly. The figures 17-20 represents the ANFIS loading data, trained data, ANFIS structure and controlled response related to Cart‘s location respectively.

Table 4. ANFIS Parameters.

Controller	ANFIS1	ANFIS2
Number of Inputs	2	2
Membership Functions Type	trimf	trapmf
Number of Membership Functions	5	9
Number of Training Data Pairs	1111	1111
Epoch Number	10	70
Number of Nodes	75	203
Number of Linear Parameters	75	243
Number of Non Linear Parameters	30	72
Total number of Parameters	105	315
Number of Fuzzy Rules	25	81
Error	2.31e-05	0.05

Table 5. Time Domain Specifications.

Pendulum Angle				
Specifications	PID	Double PID	LQR	ANFIS PD+I
Rise time	330.50	0.67	0.95	0.001
Settling time	381.06	185.48	38.43	36.49
Overshoot	7.89	0	0	0
undershoot	0.01	0	0	0
Peak	0.03	0.03	0.08	0.02
Peak time	12	25	14	12
Cart Position				
Specifications	PID	Double PID	LQR	ANFIS PD+I
Rise time	234.50	40.95	7.27	3.37
Settling time	317.73	237.79	34.62	8.95
Overshoot	0	3.38	0.02	0.62
undershoot	1.18	9.64	27.37	0
Peak	0.85	0.10	0.1	0.10
Peak time	325	103	54	10

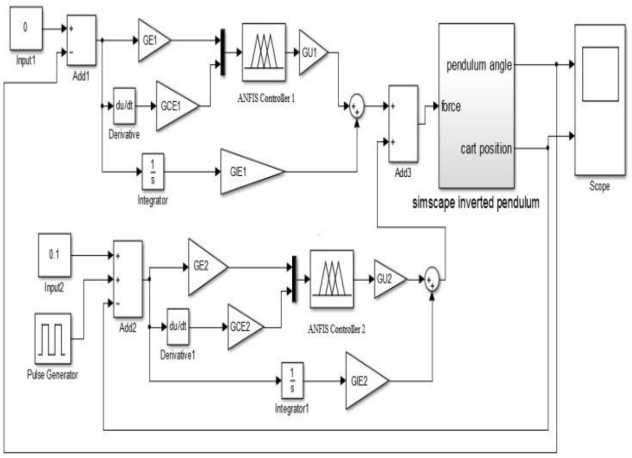


Fig.12. Simulink model of ANFIS PD+I Controller.

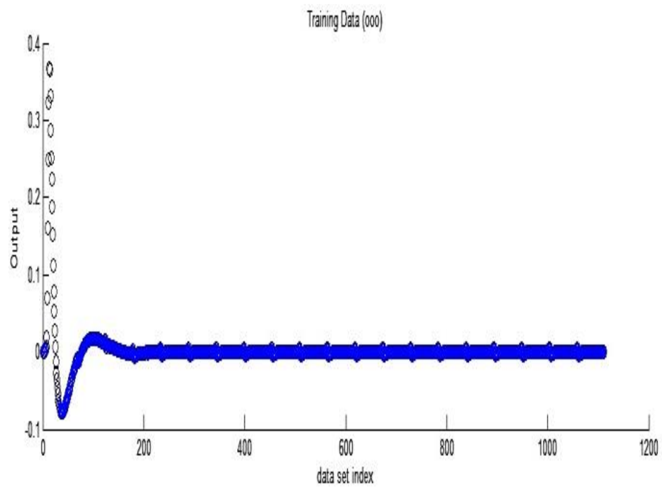


Fig. 13 ANFIS-Loading Data of Pendulum Angle.

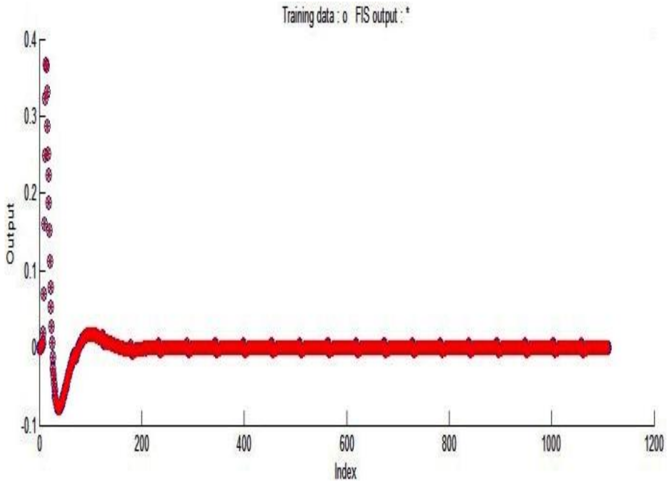


Fig. 14. ANFIS-Trained data of Pendulum Angle.

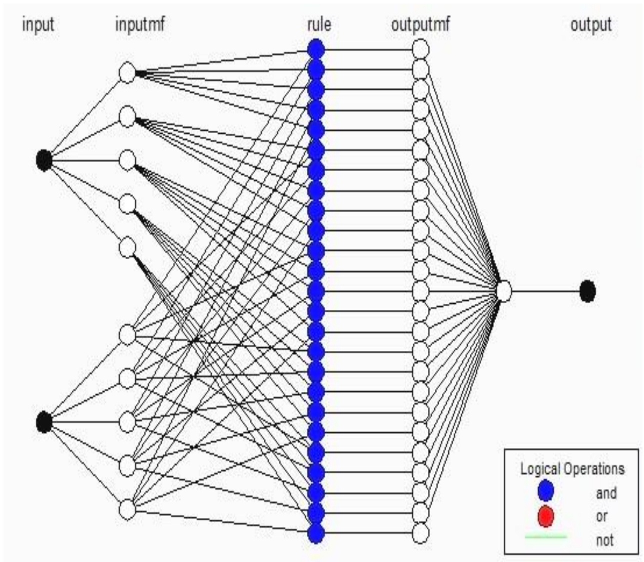


Fig. 15. ANFIS Structure of Pendulum Angle.

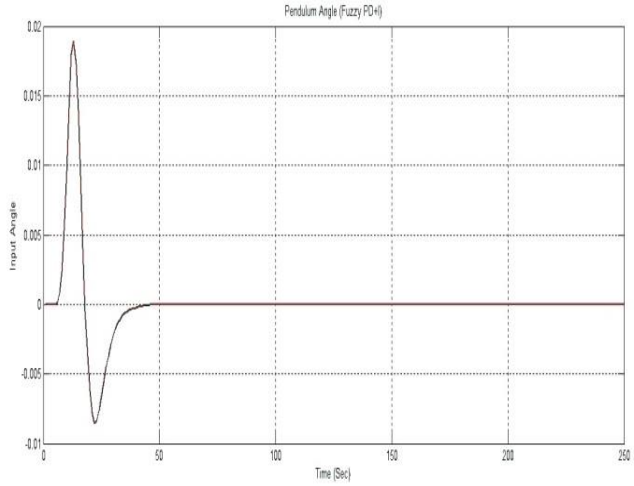


Fig. 16. ANFIS PD+I Controlled Pendulum Angle Response.

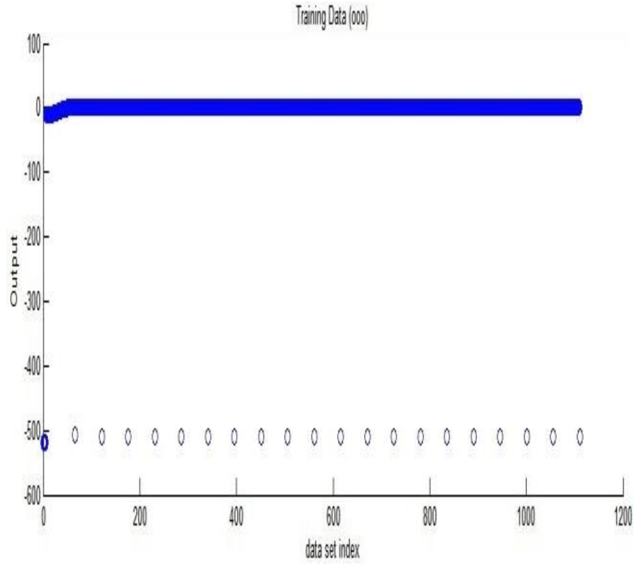


Fig. 17. ANFIS-Loading Data of Cart position.

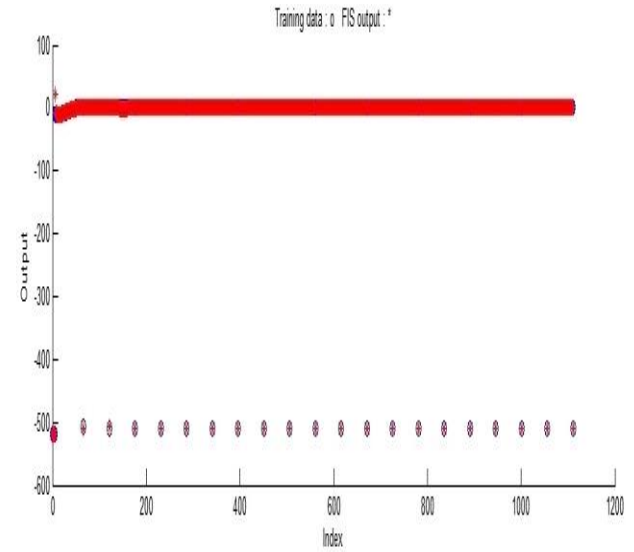


Fig. 18. ANFIS-Trained data of Cart Position.

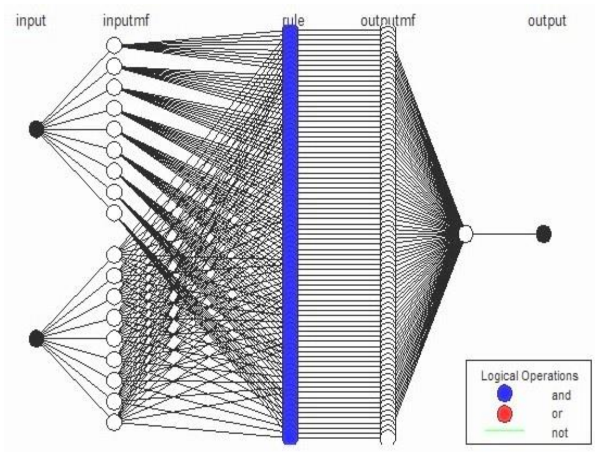


Fig. 19. ANFIS Structure of Cart Position.

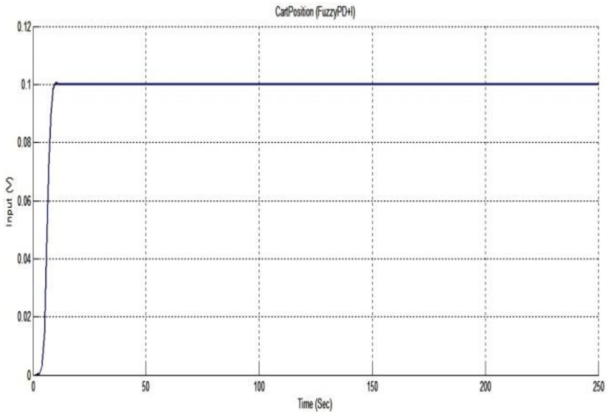


Fig. 20. ANFIS PD+I Controlled Cart Position Response.

7. CONCLUSION

The Simscape form of wheeled inverted pendulum is designed as of equations of motions and control through controllers like PID, LQR, Double PID and ANFIS PD plus I controller for comparative investigation. Sensitivity analysis is performed to analyse the impact of input parameters of the Wheeled Inverted Pendulum. The Mass of Pendulum (M_2), Length of Pendulum from the hinge point (L) and Input Force to the Cart (F) are the three input factors that influence the behaviour of Wheeled Inverted Pendulum. Based on the time domain specifications, ANFIS PD plus I controller shows less deviation in pendulum angle and it becomes the best among the other controllers. Also, rise time and settling time of ANFIS PD plus I Controller shows superior performance. In future, the real time hardware model of Wheeled Inverted pendulum robot will be demonstrated through Arduino Yun controller.

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