**Robust Adaptive Trajectory Tracking Sliding Mode Control for Industrial Robot Manipulator using Fuzzy Neural Network**

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***Abstract*— This paper presents a control method for a two-link industrial robot manipulator system that uses Fuzzy Neural Networks (FNNs) based on Sliding Mode Control (SMC) to investigate joint position control for periodic motion and predefined trajectory tracking control. The proposed control scheme addresses the challenges of designing a suitable control system that can achieve the required approximation errors while ensuring the stability and robustness of the control system in the face of joint friction forces, parameter variations, and external disturbances. The control scheme uses four layers of FNNs to approximate nonlinear robot dynamics and remove chattering control efforts in the SMC system. The adaptive turning algorithms of network parameters are derived using a projection algorithm and the Lyapunov stability theorem. The proposed control scheme guarantees global stability and robustness of the control system, and position is proven. Simulation and experiment results from a two-link IRM in an electric power substation are presented in comparison to PID and AF control to demonstrate the superior tracking precision and robustness of the proposed intelligent control scheme.**

*Keywords*— robot manipulators; fuzzy neural network; sliding mode control; robust adaptive control

# Introduction

Robot manipulators are complex systems that are prone to uncertainties in their dynamics, such as external disturbance, nonlinear friction, highly time-varying, and payload variation, which can deteriorate the system performance and stability. Therefore, achieving high performance in trajectory tracking is a challenging task. To overcome these problems, various control methods have been proposed, such as adaptive control, intelligent control, sliding mode control, and variable structure control [1-18]. Many studies on intelligent controllers based on fuzzy logic have been conducted over the last decade [19-26]. Fuzzy logic is commonly used in robot manipulators to achieve good control performance over uncertainties that cannot be described precisely by mathematical models.

In [22], an adaptive fuzzy controller based on sliding mode is proposed for tracking the trajectory of robot manipulators with unknown nonlinear dynamics. A theoretical justification for the fuzzy approximator was provided by demonstrating that it can approximate the robot's nonlinear dynamics in the vicinity of the switching hyper plane when the representative point and derivative are used as inputs. Thus, the fuzzy controller design can be greatly simplified, while the fuzzy control rules can be obtained initially using the SMC's reaching condition. In [23], fuzzy mathematical principles, a vast field, are developed by replacing sets in classical mathematical theory with fuzzy ones. In this way, all classical mathematical branches can be fuzzed. In [27], for the purpose of compensating for friction in motion control systems, a dynamic friction structure based on a local modeling approach has been proposed The suggested structure makes no claims to accurately replicate intricate friction-driven phenomena, but the nonlinear integral gain and the linearity of the local models make the observer's design and implementation easier. Then, to counteract the effects of imprecise friction compensation, the controller can be robustly synthesized using linear matrix inequalities. In [28], a self-organizing fuzzy radial basis function neural network controller, which uses an radial basis function network to regulate the parameters of the self-organizing fuzzy controller in real time to perfect values for robotic motion control, has been successfully developed for robotic system. It eliminates the difficulties of finding approximate parameters for designing a self-organizing fuzzy controller and the difficulties of the determining suitable membership functions and fuzzy rules for designing a fuzzy logic controller. However, most proposed adaptive fuzzy controllers are difficult in building suitable fuzzy control rules, membership function, and how to guarantee the system stability is a challenge problem to be solved. Recently, much scheme has been done on using NNs to provided online learning algorithms and deal with unmodeled unknown dynamics in robot model [29-43]. In [40], an approach and a systematic design methodology are presented to adaptive motion control based on NNs for high performance robot manipulators, for which stability conditions and performance evaluation have been given. The neuro controller includes a linear combination of a set of off-line trained NNs, and an update law of the linear combination coefficients to adjust robot dynamics and payload uncertain parameters. In [41], a model predictive control scheme is proposed for missile interception. Based on the tracking kinematics, the proposed model predictive control approach can handle a formulated quadratic programming problem using a neuro dynamic optimization approach. The applied neural networks can make the formulated constrained quadratic programming converging to the exact optimal values. In [42], the authors presented a neural network based on terminal SMC for robot manipulators including actuator dynamics. In the proposed control scheme, the RBFNNs are adopted to approximate the nonlinear dynamics of the robot manipulators. Meanwhile, a robust control term is added to suppress the modeling error and estimate the error of the NNs. The convergence and stability of the closed loop system can be guaranteed by Lyapunov theory. In [43], the problems of dynamic model and trajectory tracking are addressed for a redundantly actuated omnidirectional robot manipulators system with uncertainties and external disturbances. In this scheme, NNs are used to identify the system dynamics directly to make the weights matrix structure compact and tuning speed fast. A partitioned NNs structure is also applied to reduce the computing burden further. However, in most of the NNs cases, the unavoidable learning procedure degrades its transient performance in the presence of disturbance, and requires a higher computing time for a larger NNs size. Moreover, the internal behavior is ambiguous to understand, and the well-known knowledge of the model is not used sufficiently, that also degrades its performance. Nowadays, fuzzy neural networks control system obtains the merits of both fuzzy system and NNs [44-68]. In [69], an adaptive fuzzy-neural-network velocity sensorless control scheme was proposed for robot manipulator to achieve high-precision position tracking. In this proposed scheme, the FNNs controller was constructed only with the joint position feedback so that all the system dynamics could be unknown and there are no strict constraints in the control design. In [70], a novel Dynamic structure neural fuzzy networks control was presented to control the joints of robot manipulators for achieving high precision position tracking. Through combining SMC and adaptive control, the proposed control scheme can take advantages of the robust and self-learning properties to deal with the approximation error. Moreover, a FNNs inherited SMC scheme [71] is also proposed to relax the requirement of detailed system information and deal with chattering control efforts in the SMC system. However, although the stability of these control systems was guaranteed, they are not robust enough to handle the short period after transient stage, and it may cause computational burden and complexity. In addition, SMC scheme has been studied by many researchers for the joint position tracking of robot manipulators because of its robustness [72-75]. The SMC is designed to reduce the effects of the approximation errors, and it uses again which is large enough to compensate the bounded uncertainties and guarantees stability and passive of nonlinear systems [76,83].The SMC generates smooth switching between the adaptive and robust modes from integration of advantages of robust and intelligent control. However, in the literature of SMC schemes, they always require the detailed system information and the corresponding uncertainty bound to guarantee the stability. Even the auxiliary control design is still necessary, and the chattering phenomena, which caused by the SMC, still exits.

In order to achieve high precision position tracking in a variety of environments, this research presented an intelligent control scheme in this paper for two link IRM in electric power substations. This scheme combines the benefits of FNNs and SMC. Lyapunov stability theory is used to demonstrate the overall system's robustness and stability. This suggested intelligent controller is more adaptable than the results that are currently documented in the literature. Additionally, the shortcomings of SMC's discontinuous control efforts—tracking errors and the chattering phenomenon—are mitigated based on the outcomes of simulations and experiments.

The remainder of the paper is structured as follows: The robust adaptive FNNs controller design is presented in Section 3. The results of the simulation and experiments for the robot manipulators system are given in section 4. lastly, the summary is drawn in section 5.

# Problem Formulation

The dynamics of an n-link IRM with external disturbance can be expressed in the Lagrange as follows:

|  |  |
| --- | --- |
|  | (1) |

Where are the vectors of joint position, velocity and acceleration, respectively.  is the symmetric inertial matrix. is the vector of Coriolis and Centripetal forces. expresses the Gravity vector. represents the vector of the frictions.  is the vector of the input unknown disturbances. And is the control input vector of joints torque. For the purpose of designing controller, several properties of the robot model (1) have been assumed as follows.

*Property 1:* The inertial matrix *M(q)* is apositive symmetric matrix and is defined by:

|  |  |  |
| --- | --- | --- |
|  | , | (2) |

With and are known positive constants and they depend on the mass of the robot manipulators.

*Property 2:* is skew symmetry matrix, in which

|  |  |  |
| --- | --- | --- |
|  |  | (3) |

*Property 3:* *, G(q)* and *F()* are bounded as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (4) |

With are positive constants.

*Property 4:* is the unknown disturbance and bounded as:

|  |  |  |
| --- | --- | --- |
|  |  | (5) |

# Design of Robust Adaptive FNNs Controller

## Structure of adaptive FNNs

The FNNs have many advantages such as optimization abilities, learning abilities and ease of incorporating expert knowledge. They integrate function of a traditional fuzzy system and the basic elements into a connectionist structure. From the structure of the FNNs, expert knowledge can be put into the network as a priori knowledge, which can increase learning speed and estimation accuracy. In this section, the FNNs are constructed to approximate the dynamics of the uncertain term *f(x)*. The structure of four layers FNNs is presented in Fig.1.

Layer 1

Layer 2

Layer 3

Layer 4

Fig. 1. The proposed FNNs structure

Layer 1:Input layer. Each node in this layer corresponds to one input linguistic variables , and only transmits directly input values to the next layer.

Layer 2: Membership layer. In this layer, each node represents the input values with the following Gaussian membership functions:

|  |  |  |
| --- | --- | --- |
|  |  | (6) |

where and are, respectively, the center and standard deviation of the Gaussian membership function of the *i*th input variable to the node of this layer, and *m* denotes the total number of membership functions.

Layer 3: Rule layer. Each node in this layer, which is described as a fuzzy rule, multiplies the inputs signal and the outputs result of the product. The output value of this layer is calculated:

|  |  |  |
| --- | --- | --- |
|  |  | (7) |

where  is the *k*thoutput of the rule layer,  is the weight between the membership layer and the rule layer, and N is the total number of rules.

Layer 4: Output layer. In this layer, each node represents the output linguistic variables, and acts as a defuzzifier. The output can be represented as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (8) |

Moreover, the output of FNNs can be rewritten in the following form as:

|  |  |  |
| --- | --- | --- |
|  |  | (9) |

Where ;

Based on the powerful approximation ability, there exists an optimal FNNs estimator to lean the nonlinear dynamic function such that

|  |  |  |
| --- | --- | --- |
|  |  | (10) |

where are the optimal parameters of respectively, is a minimum approximation error vector, and is bounded by a positive real constant as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (11) |

*Assumption 1:* The norms of the FNNs optimal weights are bounded as follows:

.

where are the positive real values.

## Robust Adaptive FNNs Controller Design

In this paper, consider the dynamics of an n- link IRM is shown in Fig. 2 can be expressed in the Lagrange as equation (1). In order to control the joint position of the robot manipulators, the architecture of the robot manipulator control system is shown in Fig. 2 is developed in this study. This paper proposed an intelligent controller which combines adaptive FNNs control and SMC to suppress the effects of the uncertainties and approximation errors. This proposed intelligent controller generates a smooth switching between the adaptive and robust modes such that it can take advantage of their attractive features of adaptive and robust control. Thus, the unknown functions of robot manipulator control system is estimated, and the stability of control system can be guaranteed.

The tracking error vector and the sliding mode function can be defined as the following equations:

Fuzzy Neural Network

Disturbances

Update laws

*sgn(s)*

*d/dt*

*d/dt*

+

*d/dt*

+



SMC robust term



Fig. 2. Architecture of the proposed robust adaptive FNNs control system

|  |  |  |
| --- | --- | --- |
|  |  | (12) |
|  |  | (13) |

where *.* It is typical to define an error metric to be a performance measure. When the sliding surface , the sliding mode is governed by the following differential equation according to the theory of sliding mode control: . The behavior of the system on the sliding surface is determined by the structure of the matric . When the error metric is smaller, the performance is better. Therefore, equation (1) can be rewritten as follows:

|  |  |  |
| --- | --- | --- |
|  | | (14) |
|  |  | (15) |

where is defined as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (16) |

For the dynamics of an n-link robot manipulator (1), the adaptive control law is proposed as:

|  |  |  |
| --- | --- | --- |
|  |  | (17) |

where is the positive definite matrix, and ; P is positive definite, is a sliding mode controller robust term that is used to suppress the effects of uncertainties and approximation errors. And is the approximation of the adaptive function , and is designed as:

|  |  |  |
| --- | --- | --- |
|  |  | (18) |

From (10) and (18), we have

|  |  |  |
| --- | --- | --- |
|  |  | (19) |

Where

.

with and are the predefined compact sets of and .

The robust term is designed as follows:

|  |  |
| --- | --- |
|  | (20) |

where is defined as: , and is defined as: , and is a positive real value.

Substituting (17) into (15) and using (19), yields

|  |  |  |
| --- | --- | --- |
|  |  | (21) |

*Theorem 1:* Consider an n-link robot manipulator represented by (1). If the adaptive update laws are designed as (22), and the robust term is given by (20), then the convergence of network parameters and the tracking error of proposed system can be assured and approached to zero.

The parameters are updated by the following learning rules:

|  |  |  |
| --- | --- | --- |
|  |  | (22) |

where is a positive adaptation rate, and are positive and diagonal square matrices.

*Proof:* Consider the following Lyapunov function candidate:

|  |  |
| --- | --- |
|  | (23) |

where ; and are positive adaptive gain matrices.

The derivative of  along to time as follows:

|  |  |
| --- | --- |
|  | (24) |

Substituting (21) into (24), and since , yields

|  |  |
| --- | --- |
|  | ­­­­  (25) |
|  |

Using *property 2*: , from the robustifying term (20) and adaptation law (22), equation (25) becomes:

|  |  |
| --- | --- |
|  | (26) |
|  |
|  |

From property 4: and equation (11): , with , equation (26) becomes:

|  |  |
| --- | --- |
|  | (27) |

Since from *Assumption 1*, we have:

Now, equation (27) becomes:

(28)

According to (28), the results exist , is a negative function, that is , and at the initial , if are bounded , then they will remain bounded with , therefore, they are also bounded with . Defining , now, equation (28) can be rewritten as:, and integrating with respect to time, we have:

|  |  |  |
| --- | --- | --- |
|  |  | (29) |

Since is a bounded function, and is a non increasing and bounded function, yields:

|  |  |  |
| --- | --- | --- |
|  |  | (30) |

Thus, by Barbalat’s lemma, it can prove that . Therefore, the stability of the system and the tracking errors are guaranteed, and converged to zero when the time tends to infinite by the adapting control law (22). This completes the *proof*.

# Simulation and Experimental Results

## Simulation Results

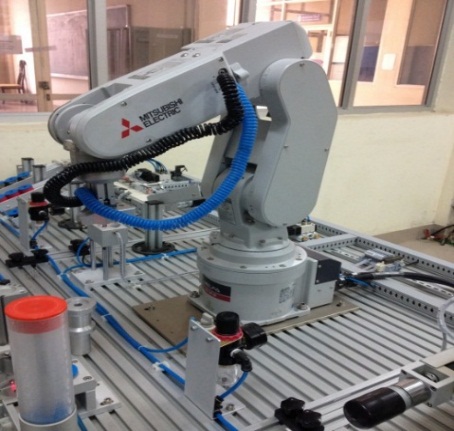
We consider the two-link IRM in electric power substation model is shown in Fig. 3, the dynamic equation can be described by using Lagrange method.

Fig. 3. The two link IRM

where

;

where are links masses; are links lengths; is acceleration of gravity.

The parameters of two link IRM in electric power substation are given by table 1.

1. Parameters of IRM

|  |  |  |
| --- | --- | --- |
| **Link** | **Mass (kg)** | **Length (m)** |
| Link 1 | 2 | 0.8 |
| Link 2 | 1 | 1 |

The object is to design control input in order to force joint variables to track desired trajectories as time goes to infinity. The desired position trajectories of the two link IRM in electric power substation are chosen by , and initial positions of joints are , and initial velocities of joints are . The tracking errors are defined as: . The parameter values used in the adaptive control system are chosen for the convenience of simulations as follows

; ;

The element of the gain matrixes in the adaptive control law (22) are selected as: ;

In the following passage, this proposed control scheme is applied to the IRM in comparison with the proportional integral differential (PID) control and the adaptive Fuzzy (AF) control [9]. The control law of the PID controller can be defined as follows

where denote proportional, integral and differential gain matrices, respectively, and they are chosen according to the Ziegler-Nichols tuning rule based on the step response of the robot manipulators control system. They were selected as

The simulation comparisons of joint position responses, tracking errors and control torques of PID, AF control and this proposed scheme in following the desired trajectories for joint 1 and joint 2 are shown in Fig. 4. From these simulation results, this proposed intelligent control system converges to the desired trajectory more quickly and achieves tracking performance better than both the case with PID and AF control. Therefore, comparing with the existing results the use of this proposed scheme with adaptation weights can effectively improve the performance of the closed- loop system. It means that the robust tracking performance of this proposed intelligent control

## Experimemtal Results

In this experimental section, two different experimental cases were conducted to investigate the chattering phenomena when the load of manipulators changed. The first experimental case assumed that 2(kg) were added to the masses of two links IRM as in Table 1 with the same desired trajectories and the other parameters as in the simulation case. The robust tracking performance of the proposed intelligent control scheme applicability and the performance of the proposed technique to consider the performance under various environments which are the parameter variation, and the change of the external disturbance were evaluated. The mechanical structure, the control system, and working principle of the IRM system are shown in Figure 5, respectively.



Fig.5. The experiment system of CDRM

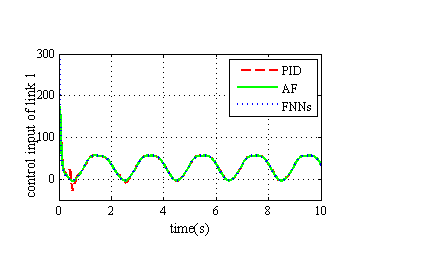
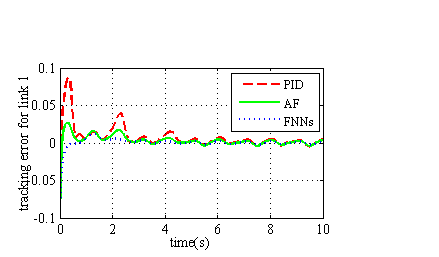
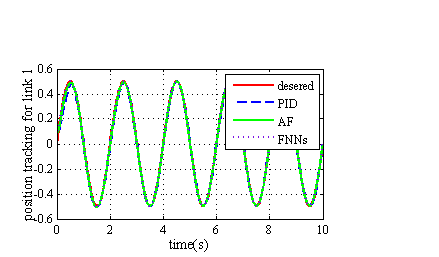
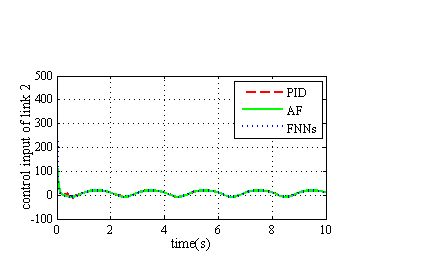
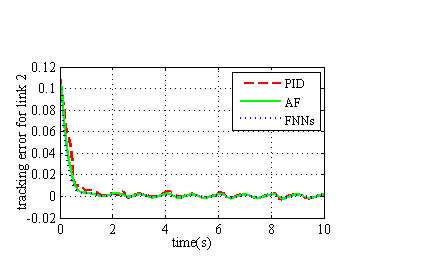
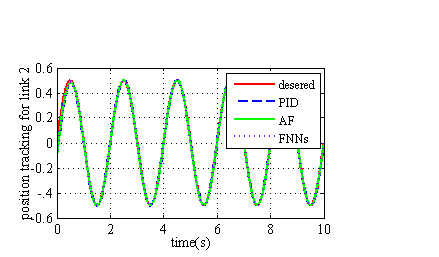
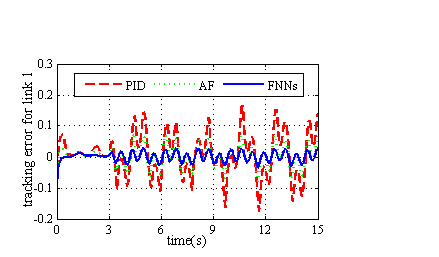


Fig. 4. Simulated results of position responses, tracking errors, control efforts of PID, AF control and the proposed control system



In the first experimental case, the masses of two links IRM were increased by 2(kg) as shown in Table 1. The desired trajectories and other parameters were kept the same as in the simulation case.

The experimental results of joint position responses, tracking errors, and control torques are presented in Figure 6. The results indicate that the responses and the tracking error norm of this proposed control scheme are significantly better than both PID and AF control methods. Additionally, Figure 6 implies that our control torques are less and smoother than the PID control and AF control in [22], which still exist the is better than the PID and AF control in [22] under parameter variation.



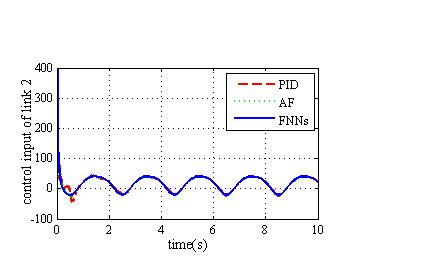
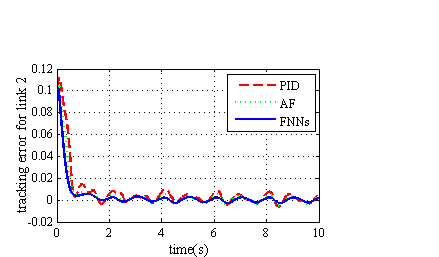
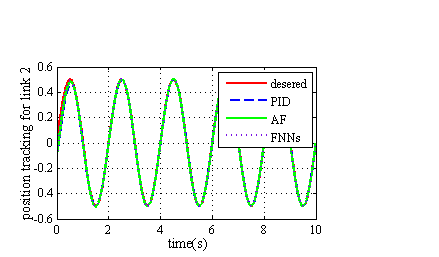
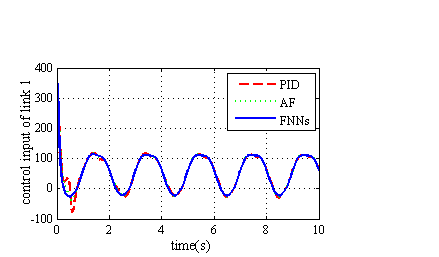
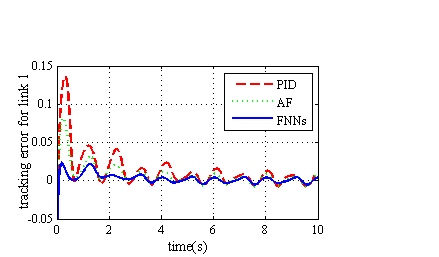
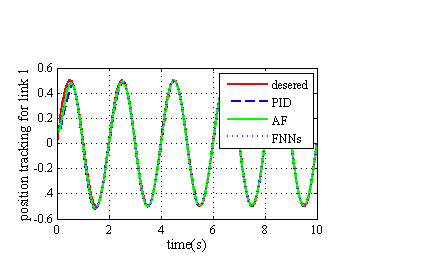
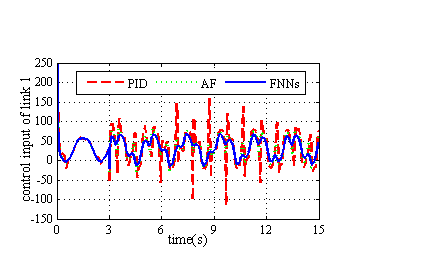
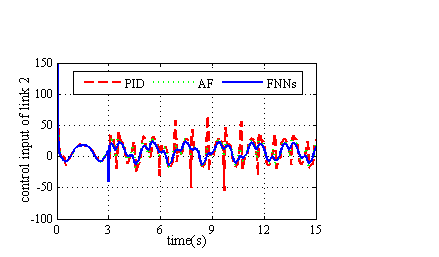
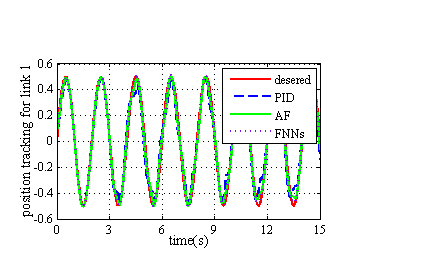
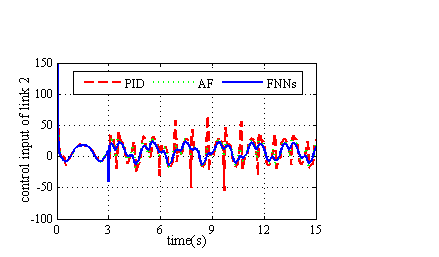
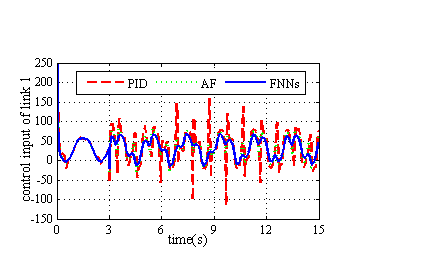
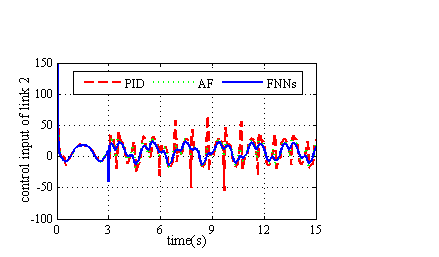
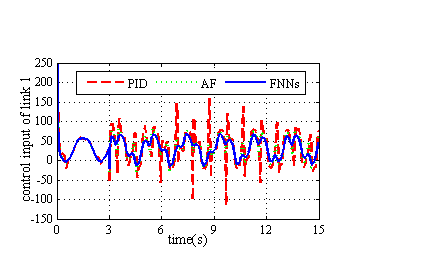


Fig. 6. Experimental results of position responses, tracking errors, and control efforts for the first case









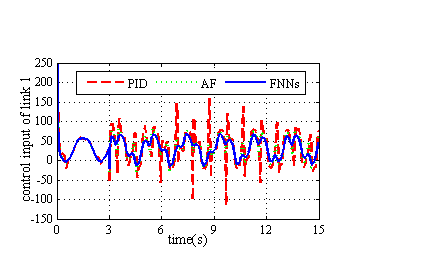
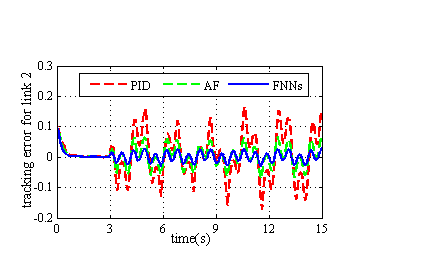
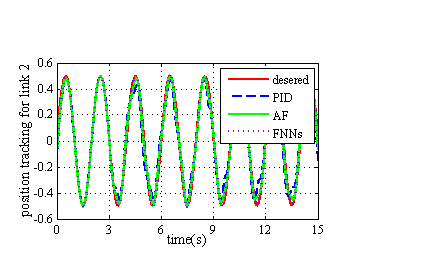
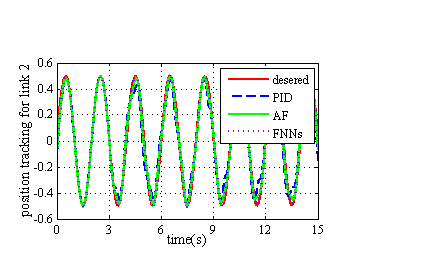


Fig.7. Experimental results of position responses, tracking errors, and control efforts for the second case







The second experimental case is assumed that the external disturbance is suddenly injected more into control system when the robot is tracking a trajectory. This happened after the first 3s of the experimental time, and all other parameters are chosen as in the simulation case. The external disturbance shapes are expressed as follows:

The experimental responses of joint position, tracking error and control torque for the second case are shown in Fig.7. From these experimental results, we can find that, the performance of PID approach is seriously affected, while the performance of this proposed intelligent control approach is only slightly affected. Therefore, the control performance and robustness of this proposed intelligent controller under external disturbance are better than PID and AF controllers [22].

# Conclusion

This paper presents a successful design of an intelligent robust adaptive trajectory tracking Sliding Mode Control (SMC) using Fuzzy Neural Networks (FNNs) to control the joints of a two-link industrial robot manipulator (IRM) in an electric power substation. The proposed control scheme achieves high precision position tracking under various environments. All the adaptive learning laws of the control system are adjusted based on the Lyapunov stability theorem, ensuring the estimation convergence, stability robustness, uniformly ultimate boundedness, and tracking performance of this proposed intelligent control system. The simulation and experiment results were conducted on a two-link IRM, and comparisons were made with the performance of PID control and AF control. Finally, as demonstrated in the illustrated simulation and experiment results, the proposed intelligent control scheme not only achieves high precision position tracking and good robustness but also removes the chattering phenomenon in the trajectory tracking control of a two-link IRM in an electric power substation under various environments, which are joint friction, parameter variation, and external disturbances, over the existing results. This proposed intelligent method can be applied as a good alternative in the existing IRM control system.

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