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Review Article

Applications of neuro fuzzy systems: A brief review and future outline

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ABSTRACT

This paper surveys neuro fuzzy systems (NFS) development using classification and literature review of articles for the last decade (2002–2012) to explore how various NFS methodologies have been developed during this period. Based on the selected journals of different NFS applications and different online database of NFS, this article surveys and classifies NFS applications into ten different categories such as student modeling system, medical system, economic system, electrical and electronics system, traffic control, image processing and feature extraction, manufacturing and system modeling, forecasting and predictions, NFS enhancements and social sciences. For each of these categories, this paper mentions a brief future outline. This review study indicates mainly three types of future development directions for NFS methodologies, domains and article types: (1) NFS methodologies are tending to be developed toward expertise orientation. (2) It is suggested that different social science methodologies could be implemented using NFS as another kind of expert methodology. (3) The ability to continually change and learning capability is the driving power of NFS methodologies and will be the key for future intelligent applications.

Contents

1. Introduction

Applications of artificial intelligence (AI) in various fields are getting more and more popular during the last decade and that is why much relevant research has been conducted. AI methods are mainly comprised of fuzzy logic, neural networks, genetic programming and hybrid approaches such as neuro fuzzy systems, genetic fuzzy systems and genetic programming neural networks etc. Neuro-fuzzy systems refer to combinations of artificial neural network and fuzzy logic in the field of artificial intelligence, which was proposed by Jang [1] in 1993. The basic idea behind this NFS is that it combines human-like reasoning style of fuzzy systems with the learning and connectionist structure of neural networks. NFS

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provides powerful and flexible universal approximations with the ability to explore interpretable IF-THEN rules. The use of NFS is proliferating into many sectors in our social and technological life. As a part of NFS research, this paper surveys the development of NFS through a literature review and classification of articles from 2002 to 2012 based on applied methodologies, domains and article types. Based on the survey, this paper explores a future research direction of NFS in various domains. The reason behind choosing this period is that many authors started to shift to neuro fuzzy domains for much improved result and a huge number of related applications were developed in this duration. This literature survey is based on a search in the keyword index and article abstract for 'NFS' on the IEEE Xplore, Elsevier, ACM digital library, Springer, Ingenta, EBSCO, Wiley Inter Science online database and many other reputed journals and conference proceedings. Based on the scope of collected articles on NFS applications, this paper surveys and classifies NFS applications into ten different categories: student modeling system, medical system, economic system, electrical & electronics system, traffic control, image processing & feature extraction, manufacturing & system modeling, forecasting & predictions, NFS enhancements and social sciences for different research and problem domains.

The rest of the paper is organized as follows. Sections 2–11 present the survey results of NFS methodologies, domains, and article types based on the above categories respectively. Section 12 presents some discussions and limitations of NFS methodologies and applications. Finally Section 13 contains a brief conclusion and future outline of NFS.

2. NFS in student modeling

Neuro fuzzy applications in educational field are getting more and more popular during the last decade (2002–2012) and that is why much relevant research has been conducted. Neuro fuzzy system has a wide range of applications in the educational field and new directions are constantly given in educational research. According to Stathakopoulou et al. [2] student modeling is consisted of two components: the student model and the diagnostic module. The student model is one of the components of an intelligent tutoring system (ITS) which provides a description of student related information such as his knowledge level, skills or even preferences while diagnosis is the inference process which results in the end updates of the student model. Student modeling includes student classification, monitoring students' actions, processing intelligent learning environment (ILE), assessing students' knowledge, evaluating students in intelligent tutoring system, modeling students in web based ITS etc. A summary of thoughts contributed by various authors in this category is described below.

During the last decade a number of researchers have contributed their innovations in this category. In the year 2003, Stathacopoulou et al. [3] presented a neural network-based fuzzy modeling approach to assess student knowledge. Authors used fuzzy logic to handle the subjective judgments of human tutors with respect to student observable behavior and knowledge, here Student knowledge is decomposed into pieces and assessed by combining fuzzy evidences, each one contributing to some degree to the final assessment. Later in 2004, they implemented a neural network and fuzzy logic based model to achieve accurate student diagnosis and updates the student model in intelligent learning system (ILS) [4]. In the same year, they presented neural network-based fuzzy model [5] to access student's motivational state in a discovery learning environment with the assistance of a group of expert teachers. In 2004, Ali et al. [6] presented a neural fuzzy inference system for modeling student in the context of web based intelligent tutoring system. Web based intelligent tutoring system provides a learner platform independence, time independence and location independence and also without the expense of one to one tutoring scopes. Later in 2006, Sevarac [7] presented a neuro-fuzzy system for student modeling. The proposed system performed classification of students based on qualitative observations of their characteristics. Next year Stathacopoulou et al. [8] implemented a neural network based fuzzy diagnostic model by monitoring students' learning style and teachers' expertise behavior. Authors used fuzzy logic to provide a linguistic description of students' behavior and learning characteristics. They used neural networks to add learning and generalization abilities to the fuzzy model by encoding teachers' experience through supervised neural-network learning. In 2009, Taylan et al. [9] proposed adaptive neuro fuzzy inference system (ANFIS) using genetic algorithm (GA) to assess student's academic performance. Recently, Iraji et al. [10] proposed student classification technique using adaptive neuro fuzzy system. Adaptive neuro fuzzy system has established itself as one of the popular modeling technique in the field of control systems, expert systems and complex system modeling. Their motivation behind the research work was to identify exceptional and week students for proper attention. The methodology, domain and article type of student modeling system are categorized in Table 1.

3. NFS in medical system

A medical system, also sometimes referred to as health care system is the organization of people, institutions and resources to deliver health care services to meet the health needs of target populations. Presently diseases in India have emerged as number one killer in both urban and rural areas of the country. It will be of greater value if the diseases are diagnosed in its early stage. Correct diagnosis of the disease will decrease the death rate due to different diseases. Many clinical tests are being done to find the presence of the disease. In last decade neuro fuzzy applications in medical system are getting huge attention and that is why much relevant research has been conducted. NFS are being used for various typical disease diagnoses like brain disorder, cardiac disease, breast cancer, alzheimer, thyroid disorder, leukemia, hypotension, heart disease etc. Following is a brief outline that shows how neuro fuzzy system has been contributing in medical disease diagnosis since 2003.

In 2003, Neagoe et al. [12] proposed fuzzy gaussion neural network to recognize the ECG signals for ischemic heart disease diagnosis with the help of applied Principal Component Analysis (PCA) and Discrete Cosine Transform (DCT). Mastorocostas and Hilas [13] in 2004 presented fuzzy neural filter for the separation of discontinuous lung sounds using dynamic orthogonal least square method. Later in 2005 Mastorocostas and Theocharis [14] presented the same fuzzy neural filter for real time separation of discontinuous sounds from lung obtained from the patients. In the same year Guler et al. [15] proposed adaptive neuro fuzzy inference system (ANFIS) model for classification of electro encephalogram (EEG) signals, which was clinically used to investigate brain disorder. Oweis et al. [16] in 2005 proved that neuro-fuzzy approach could be one of the important modalities in image processing, especially in the biomedical scenario where most diagnostic techniques rely on imaging. The presented pixel classification tool was a highly useful, powerful, and independent of any expert or any prior knowledge. After a couple of years Stavrakoudis et al. [17] presented the fuzzy neural filter to perform separation of lung sounds involving the patients with pulmonary pathology. They used Takagi–Sugeno–Kang (TSK) recurrent network for this purpose. In the same year (2007), Polat and Gunes [18] paid their attention for diabetes patients. Using expert system, Principal Component Analysis (PCA) and proposed ANFIS, they started to improve

Table 1
Student modeling system.

Authors/years	Methodology	Domain	Article type
Stathacopoulou et al. [3] (2003)	Neuro fuzzy (NF) approach	Student diagnosis	Simulation
Stathacopoulou et al. [4] (2004)	NF Rules	Student diagnosis in ILS	Simulation
Ali et al. [6] (2004)	ANFIS	Student modeling	Simulation
Stathacopoulou et al. [5] (2004)	Fuzzy neural network	Student's motivation detection	Descriptive
Sevarac [7] (2006)	Neuro-fuzzy systems	Students modeling	Classification
Stathacopoulou et al. [8] (2007)	FL, NN	Students learning assessment	Experimental
Taylan et al. [9] (2009)	ANFIS, genetic algorithm	Student's performance	Analytical
Iraji et al. [10] (2012)	ANFIS, LVQ rules, GA	Student Classification	Simulation
Macwan & Sajja [11] (2012)	Neuro-fuzzy technique	Employee evaluation	Development

Table 2
Medical system.

Authors/years	Methodology	Domain	Article type
Neagoe et al. [12] (2003)	Fuzzy-Gaussion neural network,	Ischemic heart disease	Experimental
Mastorocostas and Hilas [13] (2004)	FNN, least square methods	Lung sound analysis	Analytical
Mastorocostas & Theocharis [14] (2005)	Recurrent filter, fuzzy neural network	Lung sounds separation	Experimental
Guler et al. [15] (2005)	Wavelet transform, ANFIS	Brain disorder	Classification
Oweis et al. [16] (2005)	NF approach	Bio-medical	Classification
Subasi [30] (2006)	Neuro-fuzzy logic technique, discrete	Epileptic seizure	Analytical
Wavelet transform			
Stavrakoudis et al. [17] (2007)	Fuzzy neural filter, TSK fuzzy network	Lung soung separation	Experimental
Polat & Gunes [18] (2007)	PCA, ANFIS, expert system	Diabetes diagnosis	Diagnosis
Sengur [19] (2008)	ANFIS, LDA	Heart disease diagnosis	Comparative
Ubeyli [20] (2009)	ANFIS, decision making, Lyapunov-exponent	ECG signal classification	Classification
Ovreiu and Simon [21] (2010)	EA, BPO, NF Rules	Cardiac disease	Simulation
Alamelumangai and DeviShree [22] (2010)	Neuro fuzzy model, PSO	Breast cancer diagnosis	Optimization
Obi and Imainvan [23] (2011)	NFI procedure	Alzheimer	Diagnosis
Obi and Imianvan [24] (2011)	NFI procedure	Leukemia	Diagnosis
Kumar et al. [25] (2011)	Fast ANFIS, LM Algorithm	Cancer diagnosis	Experimental
Agboizebeta and Chukwuyeni [26] (2012)	Neuro-fuzzy inference (NFI) system	Thyroid detection	Demonstrating
Agboizebeta and Chukwuyeni [27] (2012)	NFI procedure	Hypotension control	Analytical
Ephzibah and Sundarapandian [28] (2012)	GA, ANN	Heart disease	Diagnosis
Khameneh et al. [29] (2012)	ANFIS	Blood disorder diagnosis	Diagnosis

diagnostic accuracy of diabetes disease. They reached to the classification accuracy point which was 89.47%, promising with regard to other classification applications. Sengur [19] in 2008 investigated the use of linear discriminant analysis (LDA) and ANFIS to determine the normal and abnormal heart valves by diagnosing heart sounds. Ubeyli [20] in 2009 presented ANFIS for ECG signal classification using Lyapunov exponents for improvement of diagnostic accuracy. Later in 2010, Ovreiu and Simon [21] focused on cardiac disease. They used biogeography based optimization (BBO), Evolutionary Algorithm (EA), neuro fuzzy rules for cardiac diagnosis. In the same year, Alamelumangai and DeviShree [22] proposed particle swarm optimization (PSO) algorithm to optimize neuro fuzzy model for ultrasound image segmentation. This system was tested for detecting the micro calcifications in breast sonograms. Obi and Imainvan [23] in 2011 analyzed Alzheimer disease diagnosis using neuro fuzzy inference procedure. In that year they also paid attention on lukemia diagnosis [24]. For diagnosis they used neuro fuzzy logic (NFL) and expert system based procedure. Kumar et al. [25] in 2011 proposed fast ANFIS to detect the occurrence of cancer. Fast adaptive neuro fuzzy inference system (FANFIS) was used along with gene ranking technique called analysis of variance (ANOVA). The learning technique used in this paper is modified Levenberg–Marquardt algorithm. Recently in 2012, Agboizebeta and Chukwuyeni [26] have focused on thyroid disorder with the help of neuro fuzzy expert system using a set of symptoms. The system designed was an interactive system that was able to interact with the patient briefing his current condition. They also proposed cognitive neuro fuzzy expert system for hypotension control [27] in the same year. Ephzibah and Sundarapandian [28] concentrated on medical system for diagnosis of heart disease. They used combination of neuro fuzzy technique and other soft computing techniques like genetic algorithm. Khameneh et al. [29] in 2012 has performed investigation using ANFIS to detect abnormality in red blood cell and classify blood samples into normal and abnormal category. Their motivation behind the research work was to identify, classify, diagnosis different type of disease for different fields. The methodology, domain and article type of medical system are categorized in Table 2.

4. NFS in economic system

An economic system can be defined as an organization where a person, country or area makes, distributes, consumes, buys or sells services and goods. This type of system has a direct impact on various governments and also on public activities. NFS can be applied in various field of economic system like state economic, stock market, toll collection, gas condensate, energy consumption, electric load forecasting, price prediction, supply chain management etc. Since the last decade, Neuro fuzzy applications in economic systems are attaining huge attention of many researchers and a number of relevant researches have been conducted. Starting from stock market to supply chain network, NFS has a wide range of applications in the economic systems, a few of those are briefly described here.

In the year 2005, Ang and Quek [31] proposed rough set-based pseudo outer-product (RSPOP) for stock market prediction. The proposed stock trading model avoids the forecast bottleneck and synergizes the time delayed price difference forecast approach with simple moving average rules for generating trading signals. Later Lin et al. [32] provided a mathematical model using neuro fuzzy approach to describe the online English auction process for final price prediction. In this paper, authors proposed a hybrid neuro fuzzy method to predict the final price in addition to exploring the complicated possibly nonlinear relationship among the auction mechanisms and final price. The empirical results showed that

Table 3
Economic system.

Authors/years	Methodology	Domain	Article type
Ang and Quek [31] (2005)	RSPOP algorithm, rough set, NF	Stock market	Experimental
Lin et al. [32] (2006)	Hybrid NF method	English auction	Experimental
Atsalakis and Valavanis [36] (2009)	ANFIS	Stock market	Simulation
Gumus et al. [35] (2009)	MILP, ANN	Supply chain network	Comparative
Kablan [33] (2009) (2011)	ANFIS	Financial trading market	Simulation
Nowroozi et al. [34] (2009)	NFS	Gas condensate	Experimental
Mordjaoui et al. [37] (2010)	NF technique, modeling	Electrical load forecasting	Industrial context
Kalbande et al. [43] (2011)	NF algorithm	Toll collection	Case study
Iranmanesh et al. [38] (2011)	LLNF	Energy consumption	Case study
Schott and Kalita [39] (2011)	NF Logic	Stock market	Experimental
Tsai and Chen [174] (2011)	Fuzzy delphi, fuzzy AHP	Tourism industry	Development
Kasa [40] (2012)	FL, NN	Economical system	Simulation
Giovanis [42] (2012)	ANFIS, Gaussian	Economic (USA)	Case study
Fang [41] (2012)	ANFIS	Financial crisis	Comparative
Liu et al. [157] (2012)	Fuzzy logic, decision analysis	Environmental management	Demonstrative
Lin et al. [154] (2012)	Kalman filter decision system	Debris flow hazard assessment	Development

neuro fuzzy system can predict the final price accurately much better than the others. Kablan [33] in 2009 focused on financial trading market. Using ANFIS model author achieved better performance in trading system. In the same year, Nowroozi et al. [34] proposed NFS for gas condensate. Gumus et al. [35] did work on supply chain network using neuro fuzzy procedure and mixed integer linear programming (MILP). Atsalakis and Valavanis [36] also directed their research on stock market using ANFIS. In 2010, Mordjaoui et al. [37] presented a short term electric load forecasting model using ANFIS for forecasting electric load in industry. Iranmanesh et al. [38] in 2011 proposed a forecast method based on local linear neuro fuzzy (LLNF) model and fuzzy transform mechanism for energy consumption. Schott and Kalita [39] also presented ANFIS in stock market prediction. Recently Kasa [40] used neuro fuzzy system and fuzzy logic for economical decision making. In the same year, Fang [41] proposed ANFIS in the application of financial crisis forecasting. Tsai and Chen [174] explored various theories related to different kinds of natural disaster risk analysis mechanisms, with the goal of establishing a rapid risk assessment model suited to the tourism industry that can be used to quickly analyze disaster-forming characteristics and risk weaknesses in local regions. Last year Giovanis [42] predicted economic crisis period in USA using two approaches: the first approach includes Logit and Probit models and the second is an adaptive neuro-fuzzy inference system with Gaussian and generalized bell membership functions. Liu et al. [157] combined three categories of research (risk assessment based, life cycle assessment based and criterion based) in an integrated framework to retrieve the benefits of these three combined categories. Lin et al. [154] aimed to develop a model for debris flow hazard assessment in Taiwan using Kalman filter decision system. Besides these, a number of researchers [141,142,145–148,150,151,153,163–166,168,173] have contributed in this category. Researchers' motivation behind this research work was to predict and solve economic crisis of various field. The methodology, domain and article type of economic system are categorized in Table 3.

5. NFS in traffic control

Neuro fuzzy system has a wide range of applications in the traffic control since last decade. Recently a number of researchers are paying their attention in this category. Road traffic control is the process which is used to describe how councils and highway authorities control use of the road network in order to achieve improvements in road safety and efficiency. Network traffic control is the process of managing, prioritizing, controlling or reducing the network traffic to reduce congestion, latency and packet loss.

During the last decade a number of researchers have given their concentration in this category. In 2005 Abdennour [44] developed neuro fuzzy system for MPEG coded video traffic control which is important for networking and internet multimedia. The reason behind this development of the system was to simplify the system design and also for fast execution. The author proved that neuro fuzzy systems could be very effective in long-term prediction of this type of traffic. Izquierdo et al. [45] in 2007, proposed neuro fuzzy approaches for dynamic classification of the road vehicles to avoid road vehicles collision. In the same year, Partouche et al. [46] presented a new approach to autonomously adapt the speed of a vehicle by learning from a human driver and using anticipation. Later, Aseri and Bagai [47] proposed ANFIS to solve the problem of rate control for Available Bit Rate (ABR) service class in Asynchronous Transfer Mode (ATM) networks. Sindal et al. [48] in 2009 developed neuro fuzzy call admission control algorithm to reduce voice data traffic in CDMA cellular network by transmitting signals as lower power level. In 2011, Abbas et al. [49] proposed neuro fuzzy system for best route selection to avoid traffic congestion. They used neuro fuzzy logic and ant colony system (ACS) algorithm for routing. The researcher's motivation behind the research work was to avoid road traffic, road accident, network congestion, video traffic and vehicles congestion. The methodology, domain and article type of traffic control categorized in Table 4.

6. NFS in image processing and feature extraction

Neuro fuzzy system has a wide range of applications in the imaging analysis. Imaging analysis is the process of extraction data or information from images by means of image processing techniques. Computers are indispensable for the analysis of large amounts of data which contains the fields of computer or machine vision and medical images for tasks that require complex computation for the extraction of quantitative information and makes use of pattern recognition, digital geometry, and signal processing. Some applications related to image processing and feature extraction include emotion recognition, image steganalysis, noisy image processing, face recognition and image compression. A brief description of works done by various authors in the last decade is presented below.

In 2005, Ioannou et al. [50] created rule based neuro fuzzy system to describe an emotion recognition system. This system combined psychological findings about emotion representation with analysis and evaluation of facial expressions. The authors classified facial expressions using a continuous 2D emotion space. Later in 2007, Thanh et al. [51] proposed a generalized fuzzy inference

Table 4
Traffic control.

Authors/Years	Methodology	Domain	Article type
Abdennour [44] (2005)	Neuro fuzzy system	MPEG video traffic	Simulation
Partouche et al. [46] (2007)	Hybrid fuzzy neural network	Road safety	Simulation
Izquierdo et al. [45] (2007)	NF approach	Vehicles collision control	Classification
Aseri and Bagai [47] (2008)	Adaptive NF mechanism	ATM network	Simulation
Sindal et al. [48] (2009)	Neuro-fuzzy algorithm	Cellular network	Comparative
Abbas et al. [49] (2011)	Neuro fuzzy logic (NFL), ACO	Road traffic control	Simulation

Table 5
Image processing and feature extraction.

Authors/Years	Methodology	Domain	Article type
Ioannou et al. [50] (2005)	Neuro fuzzy rule based system	Emotion recognition	Classification
Liu and Sung [52] (2007)	NFS, SVM	Image steganalysis	Experimental
Thanh et al. [51] (2007)	GFIS, Mamdani & T–S fuzzy model, NN	Noisy image processing	Simulation
Makhsoos et al. [54] (2009)	Fuzzy logic, neuro fuzzy system	Face recognition	Experimental
Marichal et al. [55] (2009)	NF approach	Feature extraction	Simulation
Chakrapani and Soundararajan [53] (2009)	ANFIS	Image compression	Simulation
Gomathi et al. [56] (2010)	ANFIS, LBP histogram	Facial expression	Experimental
Montazer et al. [57] (2010)	MLP, NFIS	Character recognition	Simulation
Lin and Chen [177] (2010)	Fuzzy model	Satellite imagery	Simulation
Sood and Aggarwal [58] (2011)	Neuro-fuzzy approach, ANFIS	Neuro-fuzzy classification	Comparative
Jafari et al. [59] (2011)	NFIS	fracture density	Estimation

system (GFIS) in noise image processing which was a multi-layer neuro-fuzzy structure that combined both Mamdani model and Takagi–Sugeno (T–S) fuzzy model to form a hybrid fuzzy system. GIFS acquired the interpretability property of the Mamdani model and stability criteria of Takagi–Sugeno model. In the same year Liu and Sung [52] presented a scheme based on feature mining and neuro-fuzzy inference system for detecting LSB matching steganography in gray scale images. Support vector machine recursive feature elimination (SVM-RFE) was proposed to obtain better detection accuracy. Chakrapani and Soundararajan [53] proposed ANFIS for fractal image compression (FIC) in spatial domain in 2009. Authors used ANFIS based network for classifying the domain cells of a gray level image based on its statistical characteristics to perform fractal image compression. This technique incorporated the concept of NN in creating the rules and produced a fuzzy model based on Takagi–Sugeno approach. In that year, Makhsoos et al. [54] did their research work on face recognition using multi layer perceptron (MLP) network by combining fuzzy logic, neural network and mixture of experts. They presented the importance of combining these two technologies (neural networks and fuzzy logic) in face recognition. Marichal et al. [55] in their paper presented an approach based on a simulated environment and the application of a Neuro-Fuzzy technique in order to extract features of the environment by ultrasonic sensors while a vehicle is moving. In the year 2010, Gomathi et al. [56] proposed neuro fuzzy approach for facial expression recognition system to recognize the human facial expressions like happy, fear, sad, angry, disgust and surprise using local binary pattern (LBP) histogram. This model reported 95.29% of classification accuracy. Montazer et al. [57] proposed a neuro-fuzzy inference engine to recognize the Farsi numeral characters. Lin and Chen [177] developed an application using fuzzy models for the monitoring of ecologically sensitive ecosystems in a dynamic semi-arid landscape from satellite imagery. Sancheza et al. [132] introduced a novel neuro-fuzzy system FasArt (Fuzzy Adaptive System ART-based) for both clustering and classification purpose which was tested on a dataset produced by UNIPEN project. Motivation of the researchers behind this research work is to reduce the noise in image, face recognition, image compression, facial expression recognition, character recognition, steganalysis in image etc. The methodology, domain and article type of image processing and feature extraction are categorized in Table 5.

7. NFS in forecasting and prediction

Forecasting and prediction is the process to predict future events and conditions and should be key decision-making elements for management in service organizations. The term 'forecasting' is sometimes reserved for estimates of values at certain specific future times, while the term prediction is used for more general estimates of values over a long period of times. During the last decade a huge number of researchers have contributed their innovations in this category and a number of research works have been conducted in recent years.

In 2005, Nayak et al. [60] proposed an adaptive neuro fuzzy inference system for river flow forecasting. Authors demonstrated the applicability of neuro fuzzy systems in developing effective nonlinear models of the rainfall-runoff process for short-term flood forecasting. Ang and Quek [61] presented a novel rough-set based neuro-fuzzy approach for forecasting stock trading difference. Lin et al. [62] in 2008 proposed ANFIS based approach to predict sea level using tide generating forces and sea surface temperature. The proposed model named tide-generating forces considering sea surface temperature and fuzzy neuro-network system (TGFT-FN). This paper presented an adaptive neuro fuzzy inference system for predicting sea level considering tide-generating forces and oceanic thermal expansion. Authors assumed that sea level is dependent on sea surface temperature. Chen et al. [178] in 2009, constructed a mathematical model for ocean environment to consider the influence of the external waves on oceanic structures. They employed Takagi–Sugeno fuzzy model in the approximation of the oceanic Structure and performed stability analysis using the Lyapunov direct method. Next year, Chen et al. [183] proposed a Takagi–Sugeno fuzzy model based controller, which can attenuate the influence of the external wave force. The controller was evaluated in terms of stability analysis and the linear matrix inequality (LMI) conditions. Later in 2011, Patil et al. [63] presented ANFIS to predict ocean wave transmission. Authors implemented ANFIS using neural network and back propagation algorithm. Chen [136] presented a Takagi–Sugeno fuzzy model for the modeling and stability analysis of oceanic structures. Author discussed vibration of the oceanic structure analytically based on fuzzy logic theory, fuzzy Lyapunov theory and a mathematical framework. Tseng et al. [140] described a critical assessment of risk control decision model based on interpretive structural modeling (ISM) and

Table 6
Forecasting and predictions.

Authors/years	Methodology	Domain	Article type
Nayak et al. [60] (2005)	ANFIS	River flow forecasting	Comparative
Ang and Quek [61] (2005)	Neuro-fuzzy approach, rough set	Stock trading forecasting	Experimental
Lin et al. [62] (2008)	ANFIS, TGFT-FN	Sea level prediction	Experimental
Chen [178] (2009)	T–S fuzzy model	Oceanic structure	Analytic
Chen et al. [183] (2010)	T–S fuzzy model, LMI	Oceanic structure	Case study
Patil et al. [63] (2011)	ANFIS	Wave transmission	Simulation
Chen [136] (2011)	Fuzzy Lyapunov theory, T–S fuzzy model	Oceanic structures	Analytic
Lin and Chen [170] (2011)	Lyapunov theory, T–S model	Community and eco system	Simulation
Tseng et al. [140] (2011)	ISM, decision making	Risk control	Experimental
Galavi et al. [65] (2012)	ANFIS, hybrid learning algorithm	Water resource forecasting	Case study
Lin et al. [144] (2012)	Fuzzy rule based decision system	Risk assessment	Development
Liu et al. [182] (2012)	Fuzzy rule based system, data mining	Environmental impact	Assessment
Sudheer and Mathur [64] (2012)	ANFIS, PSO	Ground water flow detection	Simulation

decision making method. ISM is an interactive learning process in which a set of different and directly related elements are structured to form a comprehensive systemic model. Lin and Chen [170] extended the Takagi–Sugeno fuzzy model representation and Lyapunov method to analyze the stability of community and ecosystem hierarchies based on a framework of ecological hierarchy. Recently, Sudheer and Mathur [64] integrated ANFIS with particle swarm optimization algorithm to achieve steady uniform flow optimal solution to a ground water flow and contaminant transport problem. Galavi et al. [65] in 2012 proposed ANFIS based method for water resource forecasting. They used hybrid learning algorithm for this purpose. Lin et al. [144] developed a fuzzy-rule-based risk assessment model of debris flows to verify the accuracy of the risk assessment in order to help related organizations reduce losses caused by debris flows in Taiwan. Authors adopted a fuzzy-rule-based decision system to determine and verify the risk of debris flows. Liu et al. [182] summarized the criteria of significance evaluation from the past review results and utilized fuzzy rule-based system to incorporate these criteria into scientific facts. They also employed data mining technique to construct an environmental impact statement for reviewing results. Besides these, a set of articles [155,156,162,169,179,185] can be included in this category, which mainly concerns about bridge health monitoring, structural damage, seismic hazard, risk analysis etc. An adaptive neuro fuzzy inference system has established itself as one of the popular modeling technique in this field. Their motivation behind the research work was to predict and forecast in different categories-such as, water resource forecasting, sea level prediction, oceanic structures, risk control etc. The methodology, domain and article type of forecasting and prediction are categorized in Table 6.

8. NFS in manufacturing and system modeling

Manufacturing system comprise of equipment, products, people, information, control and support functions for the competitive development to satisfy market needs. The term may refer to a range of human activity, from handicraft to high tech, but is most commonly applied to industrial production in which raw materials are transformed into finished goods on a large scale. Manufacturing takes turns under all types of economic systems. System modeling concerns modeling the operation of an unknown system from a set of measured input output data and has a wide range of applications in various areas such as control, power systems, communications, and machine intelligence. Systems modeling may be used in different ways as part of a process for improving and understanding of a situation, identifying problems or formulating opportunities and supporting decision making. In business and IT development the term "systems modeling" has multiple meaning such as functional modeling, business process modeling, enterprise modeling etc. Applications in this category includes autonomous vehicles, gear industry, underwater robotics, anti lock braking system, supply chain management, unmanned flight control, pneumatic system, software development time estimation, time varying system etc.

During the last decade a number of researchers have contributed their innovations in this category. Kim and Yuh [66] in 2002 described fuzzy membership function based neural network for autonomous underwater vehicles of which the dynamics were highly coupled, non-linear and time varying. They achieved this by using on-line training algorithm with neural network. Then in 2004, Wang et al. [67] developed a neuro fuzzy diagnostic system for monitoring gear function. They used constrained gradient reliability algorithm to facilitate decision making process which significantly improved the diagnostic accuracy. Chen et al. [184] extended the Takagi–Sugeno (T–S) fuzzy model representation for the stability analysis of nonlinear interconnected systems with multiple time-delays using linear matrix inequality (LMI) theory. In the year 2005 many researchers [68–72,137,138] started their journey in this category. Kim et al. [68] started working on underwater vehicle dynamics using NF controller. They described a fast on-line neuro fuzzy controller for underwater robots of which the dynamics are highly nonlinear, coupled, and time-varying. The neuro fuzzy controller was based on the Fuzzy membership function neural network (FMFNN) with varying learning rate. Roy [69] proposed an approach based on adaptive neuro fuzzy inference system for predicting surface roughness of the workpiece in turning operation for set of given cutting parameters such as cutting speed, feed rate and depth cut mainly used in manufacturing industry. Ouyang et al. [70] developed a TSK-type neuro fuzzy network technique for deriving a model from a given set of input-output data for system modeling problems. Kaitwanidvilai and Parnichkun [71] in their paper investigated two types of controller: adaptive neuro fuzzy model reference controller (ANFMRC) and hybrid ANFMRC to enhance the controller performance for the pneumatic system. Pneumatics is a section of technology that deals with the study and application of pressurized gas to produce mechanical motion mainly used in industries and factories. Yang et al. [72] developed a neuro-fuzzy controller with self-organized optimal fuzzy rules and membership functions to illustrate the effectiveness of the neuro fuzzy system on vibration control of a hard spring system. Hsiao et al. [137] derived a stability criterion for nonlinear multiple time-delay interconnected systems via Lyapunov's direct method. Authors proposed a systematic design using Takagi–Sugeno fuzzy controller to ensure the stability of nonlinear multiple time-delay interconnected systems. To overcome the effect of modeling errors between nonlinear multiple time-delay subsystems and Takagi–Sugeno fuzzy models with multiple time delays, Hsiao et al. [138] proposed a robustness design of fuzzy control using a model-based approach and Lyapunov's direct method. In 2006, Raad and Raad [73] developed neuro fuzzy controller to carry out adaptive channel reservation in micro-cellular networks with general cell dwell times and call

Table 7
Manufacturing and system modeling.

Authors/years	Methodology	Domain	Article type
Kim and Yuh [66] (2002)	Fuzzy membership function-based neural Networks (FMFNNs), on-line learning.	Autonomous underwater Vehicles	Simulation
Wang et al. [67] (2004)	Neuro fuzzy system	Gear industry	Industrial context
Chen et al. [184] (2004)	T–S fuzzy model, LMI	Nonlinear systems	Simulation
Kim et al. [68] (2005)	NF controller	Underwater robotics	Simulation
Roy [69] (2005)	ANFIS	Surface roughness	Comparative
Ouyang et al. [70] (2005)	FNN, TSK model	System modeling	Experimental
Kaitwanidvilai and Parnichkun [71] (2005)	Hybrid adaptive NF model	Pneumatic system	Industrial context
Yang et al. [72] (2005)	NN, FL	Electrical plant	Experimental
Hsiao et al. [137] (2005)	Takagi–Sugeno (T–S) fuzzy controller	Non linear time delay systems	Case study
Hsiao et al. [138] (2005)	Takagi–Sugeno (T–S) fuzzy models	Non linear time delay systems	Case study
Mastorocostas et al. [85] (2005)	Fuzzy neural filter	System identification	Simulation
Kim et al. [86] (2005)	Adaptive neuro fuzzy systems,	Robotic systems	Demonstrative
Raad and Raad [73] (2006)	Neuro fuzzy controller	Micro-cellular network	Case study
Li et al. [87] (2006)	Adaptive neuro fuzzy controller	Robot modeling	Simulation
Astudillo et al. [88] (2006)	Tracking controller, type-2 fuzzy logic	Mobile robot	Simulation
Tettey and Marwala [89] (2006)	T–S fuzzy model	Conflict management	Demonstrating
Chen [175] (2006)	T–S fuzzy model	Stability conditions	Simulation
Vesselenyi et al. [74] (2007)	Fuzzy-neural controller, force-position	Robotic grinding operation	Experimental
Marza et al. [75] (2008)	Neuro fuzzy system	Software development	Estimation
Topalov et al. [77] (2009)	NFS, VSS learning algorithm	Anti lock braking system	Simulation
Topalov et al. [76] (2009)	Adaptive NF control	Anti lock braking system	Simulation
Seyedhoseini et al. [78] (2010)	ANFIS	Supply chain management	Case study
Kurnaz et al. [79] (2010)	ANFIS	Unmanned flight control	Simulation
Chen [167] (2010)	Fuzzy Lyapunov method, LMI	Stability analysis	Illustrative
Chen [172] (2010)	T–S fuzzy model, LMI	Nonlinear structural systems	Simulation
Perez et al. [131] (2010)	ANFIS, Neuro-fuzzy controller	Autonomous vehicles	Development
Farooq et al. [81] (2011)	NFS	Vehicle speed control	Experimental
Topalov et al. [82] (2011)	NFS, Sliding mode incrimental learning algorithm	Antilock braking system	Simulation
Abiyev et al. [80] (2011)	Type 2 fuzzy logic, NFS	Time varying system	Simulation
Chen et al. [139] (2011)	Fuzzy system, GA	Multivariable system control	Demonstrative
Chen [176] (2011)	NN, T–S model	Nonlinear systems	Development
Kayakan et al. [90] (2012)	SMC based learning algorithm, adaptive neuro-fuzzy network.	Robotics system	Simulation
Mahdaoui et al. [83] (2012)	NF diagnosis, TSK/Mamdani Model	Manufacturing	Diagnosis
Kayacan et al. [84] (2012)	T2 FNN	Tractor industry	Simulation
Chen [161] (2012)	Fuzzy Lyapunov method, T–S model	Nonlinear time delay systems	Simulation
Yeh et al. [181] (2012)	T–S fuzzy model, NN	Time delay system	Development

holding times where handover rates were expected to be high and non-poissonian. Chen [175] provided the stability conditions and controller design for a class of structural and mechanical systems represented by Takagi–Sugeno fuzzy models. Vesselenyi et al. [74] in 2007 presented some modeling applications on a pneumatic actuator containing a force and a position sensor. Later in 2008, Marza et al. [75] aimed at building and evaluating a neuro-fuzzy model to estimate software projects development time which is one of the challenging tasks for software developers. Authors used MATLAB 7.4 to process the fuzzy logic, neural network and neuro-fuzzy systems. Topalov et al. [76] presented a paper using a new neuro-fuzzy adaptive control approach for development of nonlinear dynamical systems, coupled with unknown dynamics, modeling errors and various sorts of disturbances. This scheme consisted of a conventional proportional plus derivative (PD) controller and a neuro-fuzzy feedback controller. After a few months the authors modified their view on anti lock braking system using a new variable structure systems-based (VSS-based) [77] on-line learning algorithm for parameters adaptation. Sayedhoseini et al. [78] in 2010 developed an approach based on adaptive neuro fuzzy inference system for measurement of agility in supply chain management while agility is accepted as a winning strategy for growth, even a basis for survival in certain business environments, the idea of creating agile supply chain have become a logical step for companies. An agile supply chain (ASC) is frequently considered as a dominant competitive advantage. Kurnaz et al. [79] in their paper described an ANFIS (adaptive neuro-fuzzy inference system) based autonomous flight controller for UAVs (unmanned aerial vehicles) with the help of three distinct operating modules implemented in MATLAB. Perez et al. [131] presented a neuro-fuzzy controller that has been applied to intelligent transportation systems. The purpose of this controller was to improve the response of a vehicle propelled by a gasoline motor. Chen [167] presented a fuzzy Lyapunov method to derive the stability conditions for an interconnected fuzzy system which represents real structural systems. Chen [172] provided a systematic and effective framework for the control of time-delayed nonlinear structural systems subjected to external excitations. He constructed global fuzzy logic controller based on T–S fuzzy controller design techniques. In 2011, Abiyev et al. [80] designed a type-2 TSK based fuzzy neural system (FNS) structure for identification of dynamic time-varying plants and equalization of time-varying channel. The usage of type-2 fuzzy sets enables the system to cope with uncertainties and to handle uncertain information effectively. Chen et al. [139] proposed an intelligent adaptive controller to handle the computational burden and dynamic uncertainty of multivariable systems to make the model-based decoupling approach simpler to implement in a real-time control system. In this study the adaptive controllers were based on fuzzy systems and the initial parameter vector values are based on the genetic algorithm. Chen [176] developed a neural-network (NN) based approach which combines Tagagi–Sugeno fuzzy control for the purpose of stabilization and stability analysis of nonlinear systems. Farooq et al. [81] designed a neuro fuzzy approach for the autonomous vehicle speed controller where the system knowledge representation and the learning mechanism made it easier to adapt the environment and control the speed to avoid the traffic congestion and collision. Topalov et al. [82] developed a Neuro-fuzzy control of antilock braking system using sliding mode incremental learning algorithm. Recently Mahdaoui et al. [83] used NF diagnostic approach along with TSK/Mamdani model and pattern recognition technique in manufacturing system for fault diagnosis. In last year (2012) Kayacan et al. [84] modeled intelligent control of tractor implement system by using type 2 fuzzy neural network (T2FNN). Authors used a novel sliding mode control theory based learning algorithm for training purpose of T2FNN. Chen [161] addressed the stability conditions for nonlinear systems with multiple time delays to ensure the stability of building structure control systems based on the fuzzy Lyapunov method. The delay independent conditions were derived via the traditional Lyapunov and fuzzy Lyapunov methods for multiple time-delay systems as approximated by the Takagi–Sugeno fuzzy model. Yeh et al. [181] proposed a method using neural-network fuzzy control mechanism for a time-delay chaotic building system where a novel stability condition was derived using the fuzzy Lyapunov method. Authors used both the Tagaki–Sugeno fuzzy model and parallel distributed compensation (PDC) scheme in the controller design. The researchers' motivation behind the research work was to improve the performance in manufacturing system and system modeling. The methodology, domain and article type of manufacturing and system modeling is categorized in Table 7.

9. NFS in electrical and electronics system

Impact of electrical and electronics system in our daily life is increasing day by day. As a result, much relevant research have been conducted in this field since last decade. Electrical systems differ around the world both in voltage and less critically frequency. It is used to connect one or more pieces of equipment to or part of a structure and designed to provide a service such as heat or electricity or water or sewage disposal. Electronic systems are groupings of electronic circuits and components that focus on the higher abstraction level concerns first and foremost, used to accomplish one or more complex functions. Both electrical and electronics systems enhance the overall operation and also improve the operator's safety, through various safety circuits and applied methods. Some of the applications implemented by NFS in the field of electrical and electronics system are thermal process, electrical drives, transformer currents, circuit theory, power system, servo system and signal processing. Used methodology for various applications and article types are grouped in Table 8. A brief description of works carried out by various authors is presented below.

During the last decade a number of researchers have contributed their innovations in this category. In 2004, Mbede et al. [91] used neuro fuzzy motion controller to generate fuzzy local planner algorithm to fit the needs of autonomous mobile manipulator that would generate the commands for robot. Mastorocostas et al. [85] started their work on signal processing using simple Fuzzy Neural Network. In the same year Khorashadi and Aghaebrahimi [92] presented a fuzzy-neuro application for an inrush detector in the differential protection of three-phase power transformers. Goel et al. [93] presented a neuro-fuzzy network where all the parameters were tuned simultaneously using Genetic Algorithms applied in thermal processing unit. Next year Chang et al. [94] proposed neural fuzzy call admission and rate controller scheme for cellular network systems to provide multirate service. They achieved low forced termination probability and high system capacity in busy traffic conditions. Chopra et al. [95] presented an article on control system using different types of methods, such as, optimization, extraction, clustering and NF technique. Mihai [96] in 2008 made an analysis of an already successful electrical drive system (based on a vector control) with the intention to generate the best data for designing a neuro-fuzzy controller for the speed loop. In the same year Fujimoto et al. [97] developed a fuzzy inference circuit that generated membership functions and inference rules automatically in the learning process. Authors designed this circuit by using hardware description language Verilog-HDL and realized on the FPGA (field programmable gate array). Later in 2009, Mihai [98,99] designed a Neural Network for getting good result in electrical drives system using ANN training procedure. In the same year, Allaou et al. [100] presented an application of adaptive neuro-fuzzy inference system control for DC motor speed optimization with swarm collective Intelligence. Kumar et al. [101] proposed a NF inference system using Mamdani type Fuzzy controller and Unified Power Flow Controller (UPFC) applied on power system. Later, Aras et al. [102] showed their interest of research on servo system using type-2 fuzzy neural system (T2FNS). The authors also presented a NF system using supervised learning algorithm in the same field of servo system [103]. Deniz et al. [135] proposed neuro-fuzzy controller (NFC) which was an intelligent controller for the control of Distribution Static Compensator's (D-STATCOM) d and q-axis currents. It is observed that the maximum work was done in this field in 2011. Yetilmezsoy et al. [104] developed an artificial intelligence based modeling scheme using the ANFIS methodology for modeling of water-in-oil emulsion formation. The proposed neuro-fuzzy model was provided resin, saturate, asphaltene, aromatics, viscosity and density data as the input variables which are readily available for most of the oils. In this year another work was done on electrical machines using SMC based algorithm by Cigdem et al. [105]. Dastranj et al. [106] structured an ANFIS using neuro fuzzy logic, neuro fuzzy controller in DC motor. Mohandes et al. [107] in 2011 used the same method and proposed same approach for experimentation on wind firm. Also Kayacan et al. [108] concentrated on neuro fuzzy system and done their work on servo system using T2FNS. Recently they presented two different research work in this field: in laboratory servo system using SMC approach, type-2 fuzzy logic system (T2FLS) [109] and another in hydraulic servo system using same approach SMC and T2FLS [110]. Coteli et al. [133] performed an experiment for controlling Distribution Static Compensator (D-STATCOM) which is a nonlinear, semi-defined and time-varying device using neuro fuzzy controller. Pfeufer and Ayoubi [134] developed a hybrid neuro fuzzy system for automobile actuator. Their motivation behind the research work was to design electrical and electronics based model.

10. NFS in NFS enhancement

According to the collected articles from different online database, it is obvious that since last decade NFS enhancement is becoming the key research area for many researchers. Some authors have concentrated on knowledge reading from fuzzy rules whereas others have contributed on flexible neuro-fuzzy systems. A brief description on the developments of NFS is given below.

In 2002, Castellano et al. [113] performed their experiment successfully to extract knowledge from data in the form of fuzzy rules using learning algorithm based on gradient descent algorithm (GDA). Valdes [114] discovered the patterns of dependency in heterogeneous multivariate dynamic systems with similarity-based neuro-fuzzy networks and evolutionary algorithms. Next year, Rutkowski and Cpalka [115] derived a neuro-fuzzy structures, which is called flexible neuro-fuzzy inference systems based on input-output data with the help of Mamdani and logical approach where along with the parameters, system type (Mamdani or logical) was also learned. In the same year, Alimi [116] presented Beta function and its main properties using central limit theorem and evolutionary algorithm. Authors showed that Beta neuro-fuzzy system was successfully implemented in VLSI circuit. Later in 2007, Chatterjee and Siarry [117] proposed linguistic hedge based neuro-fuzzy classifier (LHBNFC) applicable for problem solving domains in fuzzy systems. They employed linguistic hedges to define the flexible shapes of the fuzzy membership functions (MFs). Authors

Table 8
Electrical and electronics systems.

Authors/Years	Methodology	Domain	Article type
Mbede et al. [91] (2004)	Adaptive neuro fuzzy motion controller, fuzzy local planner algorithm	Mobile system	Experimental
Goel et al. [93] (2005)	NN, GA	Thermal process	Simulation
Khorashadi and Aghaebrahimi [92] (2005)	NF approach	Transformer currents	Simulation
Mastorocostas et al. [85] (2005)	Fuzzy neural network (FNN)	Signal processing	Simulation
Chang et al. [94] (2006)	Neural fuzzy call admission and rate controller	Mobile network	Simulation
Chopra et al. [95] (2007)	NF technique, optimization	Control system	Simulation
Toosi and kahani [111] (2007)	Neuro-fuzzy approach, GA	Networking	Classification
Fujimoto et al. [97] (2008)	NFS, back propagation algorithm	Circuit theory	Development
Mihai [96] (2008)	NF controller	Electrical drives	Analytical
Kumar et al. [101] (2009)	UPFC, mamdani approach	Power system	Simulation
Allaou et al. [100] (2009)	ANFIS, PSO algorithm	Dc motor	Simulation
Mihai [98] (2009)	ANN training procedure	Electrical drives	Simulation
Mihai [99] (2009)	Neuro-fuzzy controller, vector control	Electrical drives	Simulation
Ansari and Gupta [112] (2010)	Neuro-fuzzy filter, least mean square (LMS) algorithm, back propagation	Cell phone	Simulation
Aras et al. [103] (2010)	Supervised learning algorithm	Servo system	Simulation
Aras et al. [102] (2010)	T2FNS	Servo system	Industrial context
Deniz et al. [135] (2010)	Neuro fuzzy controller	D-statcom	Experimental
Cigdem et al. [105] (2011)	SMC based algorithm	Electrical machine	Experimental
Yetilmezsoy et al. [104] (2011)	Adaptive NF approach	Water-in-oil emulsion	Experimental
Kayacan et al. [108] (2011)	T2FNS	Servo system	Simulation
Mohandes et al. [107] (2011)	ANFIS, NFS	Wind firm	Experimental
Dastranj et al. [106] (2011)	ANFIS, NF controller	DC motors	Simulation
Kayacan et al. [110] (2012)	SMC approach, type-2 fuzzy	Hydraulic servo system	Simulation
Kayacan et al. [109] (2012)	SMC approach, type-2 fuzzy	Laboratory servo system	Simulation
Coteli et al. [133] (2012)	Neuro fuzzy controller	D-statcom	Experimental

used PSO to simultaneously tune the shape of the fuzzy MFs. Again at that time, Serra and Buttura [118] presented an algorithm known as instrumental variable QR algorithm for neuro-fuzzy identification of multivariable discrete-time nonlinear dynamic systems. Later, Juarez et al. [119] described the neural fuzzy digital filtering properties in real-time sense using simple fuzzy logic. Zanchettin et al. [120] performed a statistical analysis to verify interactions and interrelations between parameters in the design of neuro-fuzzy. Nowicki [121] presented an approach to fuzzy classification in the case of missing data using rough-neuro-fuzzy classifier in 2010. In same year, Cetisli [122] developed an adaptive neuro-fuzzy classifier (ANFC) using linguistic hedges (LH). Chen et al. [171] proposed an intelligent adaptive controller using genetic algorithm for handling two main difficulties in a neural network controller which are the selection of most appropriate initial values for the parameter vector and overcoming the coupling effect in multi-variable system control. Chen and Chen [180] proposed a method for stability analysis using a GA-Based adaptive neural network controller (ANNC). Recently, Wu et al. [123] has done a comparison between fuzzy inference system (FIS) and neural network models with some examples and introduced circuit implementations of NFS. Kayacan et al. [124] proposed a novel learning algorithm to train type-2 fuzzy neural networks using variable structured system (VSS) approach. In their study, authors tuned the network weights instead of trying to minimize the error function. Sigdem et al. [125] in 2011 presented sliding mode control theory-based learning algorithm to train the fuzzy neural networks in a feedback-error-learning structure. Khanesar et al. [126] continued their research endeavor for improvement of NFS. They explored an online tuning method for the parameters of a fuzzy neural network using variable structure systems theory. Same authors investigated a new training approach for type-2 fuzzy neural networks based on the Levenberg–Marquardt algorithm [127]. While conventional gradient descent algorithms used only the first order derivative,

Table 9
NFS enhancement.

Authors/Years	Methodology	Domain	Article type
Castellano et al. [113] (2002)	GDA, NF model	Knowledge reading	Simulation
Valdes [114] (2002)	Similarity-based NF networks, EA	Time series model	Experimental
Rutkowski et al. [115] (2003)	Mamdani and logical NF approach	Flexible neuro fuzzy	Simulation
Alimi [116] (2003)	Central Limit Theorem, NFS, EA	Beta NF System	Simulation
Nauck [128] (2003)	Neuro-fuzzy method, learning rule	Fuzzy data analysis	Analytical
Chatterjee and Siarry [117] (2007)	LHBNFC	Adaptive neuro-fuzzy	Demonstrating
Serra et al. [118] (2007)	IV-QR algorithm, FIS	Online identification	Simulation
Juarez et al. [119] (2008)	FL, NN	Neural fuzzy filtering	Simulation
Zanchettin et al. [120] (2010)	ANFIS, FNN	Parameters interaction	Analytical
Nowicki [121] (2010)	rough neuro fuzzy classifier	Missing data	Classification
Cetisli [122] (2010)	ANFC, LH	Adaptive neuro-fuzzy	Simulation
Chen et al. [171] (2010)	Adaptive neural network controller, GA	Neural network controller	Simulation
Chen and Chen [180] (2010)	ANNC, GA	Neural network controller	Simulation
Wu et al. [123] (2011)	FIS, NN model	Neuro-fuzzy model	Introductory
Kayacan et al. [124] (2011)	Interval T2FNN, VSS	Fuzzy neural network	Simulation
Sigdem et al. [125] (2011)	Fuzzy neural network, VSS,	Parameter tuning	Development
Khanesar et al. [126] (2011)	FNN, online tuning method Luapunov function approach	Membership function Evaluation	Simulation
Khanesar et al. [127] (2011)	T2FNN, Levenberg–Marquardt algorithm	Faster training of FNN	Development
Chen [159] (2011)	Fuzzy Lyapunov method, LMI	T–S fuzzy model	Simulation
Chen [160] (2011)	NN, LDI	Nonlinear T–S model	Review
Chen et al. [158] (2012)	Fuzzy Lyapunov method, LMI	T–S fuzzy model	Simulation

the authors used both first and the second order derivatives, which produced a faster training procedure. Chen [159] presented stability conditions for a T–S fuzzy model using fuzzy Lyapunov methods where the fuzzy Lyapunov function was defined by fuzzy blending quadratic Lyapunov functions. Chen [160] presented a (NN)-based approach to represent a nonlinear Takagi–Sugeno system. Author utilized a linear differential inclusion (LDI) state-space representation to deal with the NN models. Recently, Chen et al. [158] addressed the stability problem of time delay Takagi–Sugeno fuzzy systems subjected to disturbances. They presented a novel delay-independent stability criterion using fuzzy Lyapunov method and linear matrix inequality (LMI) theory to ensure the asymptotic stability of the time delay T–S fuzzy systems. Applied methodology, domain and article type of related authors are listed in Table 9.

11. NFS in social sciences

Knowledge required for social regulation can be of two types: explicit and tacit [130]. Explicit knowledge relates to the community culture indicating how things work in the community based on social policies and procedures. Tacit knowledge is ethics and norms of the community. The former could be codified, stored and transferable in order to support decision making, while the latter being based on personal knowledge, experience and judgments is difficult to codify and store.

As per our knowledge no such contribution of NFS is found in social sciences since last decade. Lazareyica et al. [129] in 2004 proposed a neuro-fuzzy modeling to support knowledge management in social regulation. They investigated neuro-fuzzy support of knowledge management in social regulation. In their model, the explicit knowledge was based on social policies and procedures to reduce smoking among youngsters. Authors expressed the tacit knowledge through the membership functions. The following table (Table 10) defines methodology, domain and article type of the concerned author.

12. Discussions and limitations

12.1. Discussion

Survey on NFS methodologies and applications are a broad category of research area in the artificial intelligence field. Category wise classification of NFS methodologies help in solving and understanding specific problems both in academic and practical fields. Various NFS methodologies have made it easier to solve typical problems in faster way and authors are giving much more attention to use those process. From this literature review it is clear that various NFS developments were focused as author's research areas, expertise and problem domains were different.

It is found that some authors are having common concept and methodologies with different application fields. However, a few authors work with different techniques and methodologies. This indicates that the trend of development on methodology is also diversified due to author's research interests and abilities in the methodology and domain. This may indicate that the development of NFS methodologies and domains is directed toward expertise orientation.

There are some applications such as student modeling, medical diagnosis, manufacturing, system modeling, forecasting, prediction, economic system, image processing, electrical, electronics, traffic control etc. are all topics of different methodologies and applications. It can be said that those applications are the major trend of NFS development and focus on different problems. This may direct development of NFS methodologies and article types toward problem domain orientation. Fig. 1 shows the impact of NFS development on various applications. Fig. 2 shows year wise development of NFS and applications.

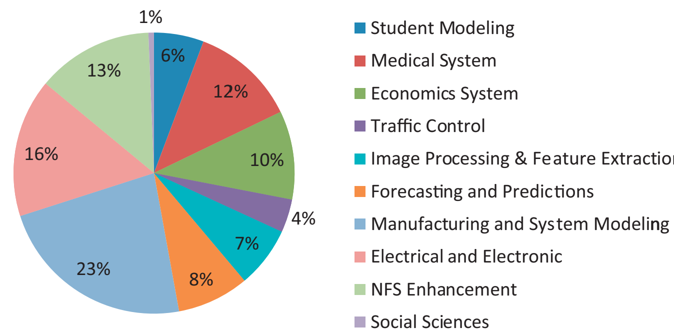

Fig. 1. Impact of NFS development on various categories.

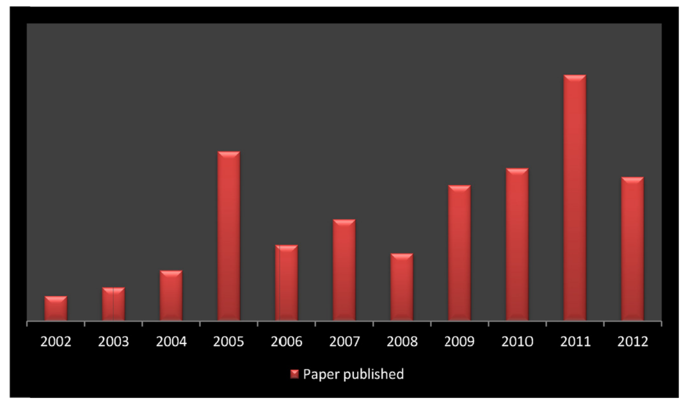

Fig. 2. Year wise development of NFS.

In this paper, most of the articles of different categories are mainly retrieved from IEEE Xplore, Elsevier, ACM digital library, Springer, Ingenta, EBSCO and Wiley Inter Science online database. This article has also reviewed a number of national and international conference proceedings including Asian Control Conference (ASCC), International Conference on Adaptive and Intelligent Systems (ICAIS) etc. for investigating various methods and applications of NFS. Yet we can't conclude that NFS methodologies are not developed in other science fields. However, we would like to see more development of NFS in different research fields published in order to broaden our horizon of academic and practice works on NFS.

According to the collected articles from various online databases, journals and conference proceedings, in the last decade, it is seen that in the year 2003 and 2004 researchers mainly focused on the student modeling system, medical system and intelligent learning system using combined approach of neural network and fuzzy logic. In 2005 their focus was widened on various systems like electrical systems, manufacturing and system modeling, imaging analysis, economic systems, prediction etc. Real evaluation of NFS has been started from this year in terms of adaptive neuro fuzzy inference system. In 2006 authors started focusing on networking system, economic system and also on intelligent learning system using hybrid neuro fuzzy model. In 2007 and 2008, researchers continued their study with more innovative ideas like adopting support vector machine along with ANFIS. In 2010, 2011 and 2012, a new direction in the neural network filed was noticed with the application of soft computing technique and advanced learning algorithms. In these years authors expressed their interest specifically in medical systems for disease classification, diagnosis and prediction. Based on our reviewed articles we can say that authors are paying their interest in applying neuro fuzzy systems to those cases where past experience and user feedback can help enormously for

Table 10
NFS in social sciences.

Authors/years	Methodology	Domain	Article type
Lazarevica et al. [129] (2004)	NF Approach, TSK model	Social regulation	Simulation

Table 11
Summary of work done in successive years.

2002	Researchers started thinking of using NFS in various applications for better outcome. Authors used NFS for autonomous underwater vehicles. Some authors investigated on knowledge extraction from data in the form of fuzzy rules.
2003	In this year a neural network-based fuzzy modeling approach was proposed to assess student knowledge base. A number of authors started thinking of using neuro fuzzy approach in medical system diagnostic system. As a new direction of NFS, flexible neuro fuzzy system was developed where not only the system parameters were updated, systems type was also updated.
2004	Authors focused on intelligent learning system (ILS) using combination of neural network and fuzzy logic. Web based intelligent tutoring system was also described in this year. NFS was used in social regulation to reduce smoking among youngsters. Authors combined Takagi–Sugeno fuzzy model with linear matrix inequality theory to analyze stability conditions of nonlinear interconnected systems.
2005	Adaptive neuro fuzzy inference system model was proposed in medical system. Neural network was combined with rough set in this year. Neuro fuzzy system was employed in networking and internet multimedia. A rule based neuro fuzzy system was described to design an emotion recognition system. ANFIS was used as basis for many researchers. Authors introduced Lyapunov's method to derive stability criteria for nonlinear systems. Effort was given to reduce modeling error between nonlinear multiple time delay systems and Takagi–Sugeno fuzzy models.
2006	Authors presented hybrid neuro fuzzy method. Neuro fuzzy controller was developed to carry out adaptive channel reservation in micro-cellular networks. Parallel-distributed compensation (PDC) scheme was utilized to construct a global fuzzy logic controller. A stability analysis was carried out not only for the fuzzy model but also for a real mechanical system.
2007	A number of authors worked to prevent road vehicles collisions applying neuro fuzzy technique. Authors used Support Vector Machine (SVM) to achieve more accuracy. Linguistic hedges were employed to define the flexible shapes of the fuzzy membership functions.
2008	Use of ANFIS was initiated in networking sector. An ANFIS based approach to predict sea level using tide generating forces and sea surface temperature was presented. Authors paid their attention to estimate software projects development time using neuro fuzzy model. A fuzzy inference circuit was developed that was able to generate membership functions and inference rules automatically in the learning process.
2009	ANFIS was the base of a number of experimentation in this year. Multi layer perceptron network (MLP) was used to identify face expression. A valuable innovation was to extract the environment features while a vehicle was moving. Adaptive Neuro-Fuzzy Inference System (ANFIS) was coupled with swarm collective Intelligence for satisfying the needs. Lyapunov direct method was used to carry out stability analysis for tension leg platform (TLP) system. Authors investigated the influence of the external waves on oceanic structures using Takagi–Sugeno fuzzy model.
2010	Authors used biogeography based optimization (BBO), Evolutionary Algorithm (EA) with neuro fuzzy rules for disease diagnosis. Particle swarm optimization (PSO) algorithm was used to optimize neuro fuzzy model. Facial expression recognition system to recognize the human facial using local binary pattern (LBP) histogram was proposed in this year. An approach based on Adaptive Neuro Fuzzy Inference System was developed for measurement of agility in Supply Chain management. For operating UAVs (unmanned aerial vehicles) a neuro fuzzy controller was developed. A number of researchers showed their interest on Type-2 Fuzzy Neural System. Research was followed to find out interrelations and interactions of various parameters in NFS design. Rough neuro fuzzy concept was introduced. Neuro-fuzzy controller was applied to intelligent transportation systems. Fuzzy Lyapunov method was used to derive the stability conditions for real structural systems. In this year attempt was taken to attenuate the influence of the external wave force using Takagi–Sugeno fuzzy controller. A number of researchers paid their attention for strengthening NFS. Neuro fuzzy controller was enhanced as an intelligent controller. Genetic algorithm was used for selecting most appropriate values for the parameter vector.
2011	Fast adaptive neuro fuzzy system was introduced in this year. Authors modified Levenberg–Marquardt algorithm to suit the complexity need. A few authors used ant colony optimization algorithm with neuro fuzzy system. A significant work was done to predict ocean wave transmission. A type-2 TSK based fuzzy neural system (FNS) structure was introduced. Neuro-fuzzy control of antilock braking system using sliding mode incremental learning algorithm was the main issue analyzed in this year. Intelligent adaptive controller was developed to handle the computational burden of complex systems. Experiments were conducted for selecting initial parameter vector values based on genetic algorithm. Interpretive structural modeling (ISM) was used to perform a critical assessment of risk control decision model. Various theories related to different kinds of natural disaster risk analysis mechanisms were explored in this year.
2012	In 2012, medical system witnessed an evolution period where patient interaction system was developed to fulfill the requirements of neuro fuzzy expert system. Many authors also concentrated on various soft computing techniques like genetic algorithm and advanced learning algorithms. Adaptive neuro fuzzy systems were used as the backbone of a number of neuro fuzzy computing systems. A revolution was initiated in economic sector with prediction of crisis period. Authors used hybrid learning algorithm for prediction and forecasting. Type 2 fuzzy neural network was one of the main ideas simulated in 2012. Authors used both the Tagaki–Sugeno fuzzy model and parallel distributed compensation (PDC) scheme in the controller design. Fuzzy-rule-based risk assessment model was developed to verify the accuracy of the risk assessment. Authors embedded data mining technique with fuzzy rule based system. In this year Kalman filter decision system was employed for hazard assessment. Asymptotic stability of the time delay T–S fuzzy systems was ensured using Lyapunov method and LMI theory.

better result. Classification of research work in different years in most sited journals and conferences are shown in Table 12. The following table (Table 11) illustrates a brief evolution of neuro fuzzy systems and applications in year wise manner.

12.2. Limitations

Research work on NFS is distributed over a wide domain and it is very much difficult to collect, study and classify the concerned articles. The authors have attempted to do a brief review of NFS articles developed in the last decade to explore how NFS has evolved in the previous years. Due to the larger domain of NFS system and applications some articles might be missing. This is one of the main limitations of this article. Also non-English publications which determine the efforts of different culture on the development of NFS are not included in this review process. The authors believe that a number of NFS methods and applications might be developed in other languages.

Since NFS is an interdisciplinary research topic so future trends of NFS developments might be the integration of different methods and techniques in promising areas. As it can inherit the learning capability from past experiences, one can easily

Table 12
Research work in most cited journal and conferences in different years.

Journal/conference	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Advances in Electrical and Computer Engineering											1
Advances in Engineering Software					1						
AMIA Annual Symposium Proceeedings		1									
Applied Energy (AE)										1	
Applied Soft Computing (ASC)										3	
Asian Control Conference (ASCC)								1		2	
Asian Journal of Control				1							
Australian Journal of Basic and Applied Sciences (AJBAS)										1	
Cognitive Systems Research (CSR)	1										
Colloids and Surfaces A: Physicochem. Engg. Aspects										1	
Computer Engineering and Intelligent Systems (CEIS)											1
Computer Methods and Programs in Biomedicine								1			
Computers and Industrial Engineering								1			
Digital Signal Processing						1					
Engineering Computations									2		
European on Conference on Modeling and Simulation (ECMS)								2			
Expert Systems with Applications (ESA)					1	2	1	2	3		
Fuel Processing Technology (FPT)								1			
Genetic And Evolutionary Computation Conference (GECCO)									1		
IEEE Conference	1		3	5	2	3		1	4	3	3
IEEE Transactions on Fuzzy Systems			1	2		1					
IEEE Transactions on Neural Networks		1			1						
IEEE Transactions on Systems, Man, and Cybernetics – Part B: Cybernetics				1							1
Proceedings of 2nd International Conference on Informatics in Control, Automation and Robotics.				1							
Information Sciences	1			1							
International Conference on Adaptive and Intelligent Systems (ICAIS)								1			
International Joint Conference on Artificial Intelligence (IJCAI)						1					
International journal of adaptive control and signal processing (IJACSP)											1
International Journal of Advanced Computer Science and Applications (IJACSA)										2	
International Journal of Applied Mathematics and Computer Science (IJAMCS)									1		
International Journal of Approximate Reasoning (IJAR)		1									
International Journal of Artificial Intelligence and Expert Systems (IJAE)										1	
International Journal of Computational Intelligence and Applications (IJCIA)									1		
International Journal of Computer Applications (IJCA)									1	1	
International Journal of Computer Science and Network Security (IJCSNS)								1			
International Journal of Computer Theory and Engineering (IJCTE)									1		
International Journal of Fuzzy Logic Systems (IJFLS)											1
International Journal of Innovative Computing, Information and Control (IJICIC)							1		1		
International Journal of Recent Trends in Engineering (IJRTE)								2			
International Journal of Scientific and Engineering Research (IJSER)										2	
International Journal of The Computer, the Internet and Management (IJCIM)							1				
International Journal on Soft Computing (IJSC)										2	
International Journal on Soft Computing, Artificial Intelligence and Applications (IJSCAI)											1
International Society of Offshore and Polar Engineers (ISOPE)				1							
International Wireless Communications and Mobile Computing Conference					1						
International Work-conference on the Interplay between Natural and Artificial Computation (IWINAC)						1					
Iranian Journal of Fuzzy Systems				1							
Journal of Computer Science and Technology (JCST)				1							
Journal of Earth System Science (JESS)							1				
Journal of Environmental Informatics											1
Journal of Geophysics and Engineering										1	
Journal of King Saud University				1							
Journal of Neuroscience Methods (JNSM)				1							
Journal of Scientific and Industrial Research (JSIR)				1							
Journal of Vibration and Control									2	3	4
Knowledge-Based Systems			1								
Mathematics and Computers in Simulation			1								
Natural Hazards										1	2
Neural Computing and Applications										2	
Neural Networks				1							
Neurocomputing										1	
Nonlinear Science and Complexity									1		
Ocean Engineering										1	
Scientific Research and Essays (SRE)											1
Task Quarterly		1									
The International Conference on Neural Information Processing (ICONIP)					1						
Tourism Management										1	
Transactions on Circuits and Systems-I: Regular Papers				1							

predict that NFS is going to be one of the pillars of scientific research.

13. Conclusion and future outline

This paper is based on literature review of NFS methodologies and applications from 2002 to 2012 using the keyword index and article title search from the online database. Although this study searches articles from online database during the last decade, recently a number of researchers [143,148–152,186,187] have contributed in this methodology which strengthen the applicability of NFS based approaches. We can conclude that a number of NFS methodologies are tending toward expertise orientation. Proposed domains are used to find out application area and article types are defined to categorize papers of different context. NFS classification can actually help us to explore applications in new unknown areas. It can be asserted that some social science, technological field, real life applications could be implemented by NFS. Integration of qualitative, quantitative and scientific methods and integration of NFS methodologies may broaden our horizon on this subject. Finally the ability to continually change and learning ability is the power of NFS methodologies and will be the NFS application domains and article types of future works.

Further development in student modeling category might include a specialized software tool for creating and adjusting student modeling, classification or reasoning components. The applicability of the evaluation procedure can further be extended by exploiting the training and generalization capabilities of the neural networks to extract information from existing student records. These records implicitly contain a true picture of the possible knowledge levels of the students and of the possible learning paths. Further investigation for the effect of the different parameters and structural features of proposed diagnostic processes is necessary in order to determine their influence in the accuracy of the assessment and adjust them accordingly. Future work might consist of other factors such as intelligence quotient (IQ) tests, different types of membership functions, different types of neural network and optimization algorithms. In future one may implement an interface by which the teacher can interact and modify the adjusting parameters of the membership functions, as well as the weights in the fuzzy relations. Intelligent helping system could be built up for students during learning interaction, based on student classification regarding their learning style provided by the model.

In medical system it should be noted that no system was designed to give required prescription of various drugs to patients for subsequent treatment, which might be expanded in subsequent research. A system of this nature that has the ability to diagnose a person suffering from specific disease should be introduced in health care delivery clinics and hospitals to help ease the work of physicians. A few suggested approaches may be enhanced by some pre-processing procedures that might boost up the characteristics of the system. Some proper adjustments in the learning schemes or the training sets can also increase the efficiency of the system, especially choosing the optimal subtractive clustering parameters. Fast adaptive neuro fuzzy systems can be applied to various applications as it takes lesser time for convergence.

In economics system there is a huge scope of future development using ANFIS. The ANFIS is a class of adaptive networks, which are functionally equivalent to the fuzzy inference system and a popular computing framework based on the concepts of fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning. ANFIS might be examined with additional fuzzy membership functions, as trapezoidal, triangular and S-shaped function among others. Moreover, GA and hybrid GA can be used, as an alternative optimization algorithm.

In future state of the art technology like microelectronics might be used to develop the hardware of any traffic control system for faster processing. Future works might be focused on the use of automatic methods for the detection of this number directly from data. Researches would lead us to the generation of more accurate and user-friendly fuzzy rules susceptible of being contrasted with a human expert.

Image processing and feature extraction acts as a sole of many experiments. In the near future generalized fuzzy inference system could be expanded to process color images. Moreover, the uniform distribution impulsive noise model would be further explained. Future extensions might include emotion recognition based on combined facial and gesture analysis. These could provide the means to create systems that will combine analysis and synthesis of facial expressions for providing more expressive and friendly interactions.

It is seen that the ANFIS was used in most of the articles included in forecasting and predictions category. Authors also used different algorithms such as hybrid learning algorithm and back propagation algorithm. The applicability of the evaluation procedure can further be extended by exploiting the training and generalization capabilities of the neural networks to extract information from existing forecasting and prediction field. The proposed TGFT-FN model would be applicable to tidal and sea level simulation in the case where tides at a point are not available so that harmonic analysis cannot be applied. The experimental results of this category are highly encouraging and suggest that an adaptive neuro fuzzy approach is viable for developing many more forecasting system like as price prediction, weather prediction etc.

Manufacturing and system modeling using NFS is proved to be one of best techniques in industry. Further research is necessary to compare efficiency of different models for measuring agility in supply chain management. Although authors have done their study in the Iranian manufacturing enterprises, different novelties of proposed procedure (that is, applying ANFIS and using different capabilities for an ASC) might be applied for surveying other real life cases. Considering enablers in agility evaluation and investigating the impact of them on capabilities could be studied in further researches. Also finding the relations between enablers and capabilities could be the focus of future research in order to design a dynamic system for ASC measurement. Articles those presented antilock braking system using neuro fuzzy controller could emphasize computational simplicity as one of its' prominent features. For any complex process, Articles those used type 1 fuzzy approach with neural network might use type 2 fuzzy approach as type 2 process consumes less number of rules than type 1 such that the number of parameters that need to be updated would be less. In future state of the art Microelectronics technology could help to develop the hardware of the vehicle moving system to achieve more accuracy. As the main problem regarding fuzzy and recurrent fuzzy neural networks that limits their application range is the difficulty of proper adjustment of fuzzy weights and biases, one can put more emphasize on the implied training algorithm. Neuro-fuzzy systems have many applications in intelligent transport systems. Neuro-fuzzy techniques could be used to model the behavior of the vehicle that would improve the current controllers in the autonomous driving. How to deal with stability and stabilization problems for T-S fuzzy systems would also be a significant area for future study.

According to the survey on NFS in the last decade, we can conclude that research interest has been diversified in this Electrical and Electronics field as well as in technique also. When some researchers working with transformer current then another's are working with electrical drives, control system, wind firm etc. Initially they were using simple neuro fuzzy logic, genetic algorithm, NF controller, optimization algorithm etc. but from 2009 they started to propose ANFIS. In 2010 it is seen that they concentrated mostly on T2FLS. That means application of proposed approach is getting modified due to time. Some research work can be done in electronics system such as, electronics circuit, laboratory, television, VLSI, electronics manufacturing systems etc. for future work, and also in electrical system such as, power plant, machines, electrical manufacturing system etc.

Further extensions of NFS might use different *t*-norms in the rule inference mechanism and could use different measurements to evaluate the degree of overlapping between fuzzy sets. As work has been done on interpretability of rule antecedents, future research might aim to deal with interoperability of rule consequents. As a future research, the selection of optimal parameters would be formulated as an evolutionary search to make the neuro-fuzzy systems fully adaptable and optimal according to user requirements.

As observed NFS have a few contributions in social regulations. Use of NFS for preparing artificial instruments especially for physically disabled person might be a revolution in coming years. It is expected that NFS will change our lifestyle in near future.

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