CHAPTER 1

INTRODUCTION

1.1 GENERAL

The trend in modern industrial and commercial systems is to integrate computing, communication and control into different levels of machine/factory operations and information processes. When dealing with a class of large-scale control applications, functional agents such as sensors, actuators, and controllers are usually spatially distributed. The mechanism of communicating information plays an important role on the stability and performance of the control systems implemented over communication networks. The traditional communication architecture for control systems, which has been successfully implemented in industry for decades, is point to point. That is, a wire connects the central control computer with each sensor or actuator point. However, expanding physical setups and functionality are pushing the limits of the point to point control system as no longer suitable to meet new requirements, such as modularity, decentralization of control, integrated diagnosis, easy maintenance and lowering of cost.

As an alternative to the point to point connections, an industrial network has been adopted where various data can be exchanged via a common communication medium. This improves the efficiency, flexibility and reliability of the integrated applications through reduced wiring and distributed intelligence, which also reduces the installation, reconfiguration, maintenance time and costs. For example the application areas such as
process automation system, automated manufacturing system and automated material handling system use communication networks.

1.2 COMPONENTS OF NETWORK CONTROL SYSTEM

The solution currently adopted to address modern control problems is to distribute the processing functions of these systems over several physical nodes, each dedicated to a part of the control process and to a group of sensors/actuators. Modern embedded systems are expected to provide more functionality and better application performance within the available resources (battery, processor, bandwidth, etc.) to avoid increasing costs. Feedback control systems wherein the control loops are closed through a communication network are called the Network Control System (NCS) which is a special class of embedded systems.

![Figure 1.1 Schematic diagram of NCS](image)

The defining feature of an NCS is shown in Figure 1.1. The information (reference input, plant output, control input) is exchanged using a network among control system components such as sensors, controllers and actuators.
1.3 CONVENTIONAL CONTROL VS NETWORKED CONTROL

Conventional control systems such as Direct Digital Control System (DDCS) and Distributed Control System (DCS) differ from an NCS within which the transfer of data from sensor to the controller or controller to the actuator is done through a communication network. In case of DDCS, the computer directly controls the process and in DCS computation is done locally and only information such as on/off signal, monitoring signal are transmitted over a serial communication network.

The communication network in the feedback loop makes the analysis and design of networked control systems, complex. In NCS, the coordination among the sensor, controller and actuator are to be ensured to maintain the system stability. Hence, the tools and methods developed in conventional control theory are to be reviewed before applying it for the NCS.

1.4 OVERVIEW OF INDUSTRIAL COMMUNICATION

In industrial communication networks, the data which are transmitted can be either real-time or non real-time, sharing a single network though they have different real-time requirements. That is, the non real-time data need assurance of delivery without error and duplication while the real-time data are concerned mostly on the time taken to reach the destination. Therefore, when building an industrial network, it is essential to configure the network to satisfy these requirements. In order to meet the real-time requirements, many industrial networks, often referred to as Field Bus, have been developed and recognized by various standard organizations since the late 1980’s.
The IEC 61158 field bus standard with several protocols including Profibus, Foundation Field Bus, and WorldFIP was announced as an international standard in the late 1990s. Although the field bus is able to satisfy the real-time requirements of field devices, they suffer from their high hardware and software cost and uncertain interoperability of multiple vendor systems. These shortfalls are hindering the adoption of field buses in numerous application areas. As an alternative to the field bus, modern communication networks which includes both wired (e.g., Ethernet) and wireless (e.g., 802.11) communications have gained some attention because of its simplicity and wide acceptance. However, modern communication network is inferior to field bus in many ways such as error checking and signaling mechanism, fault-tolerant features, reliable data transfer and so on. This is because different field bus protocols are developed as application specific solutions, whereas the modern communication networks are not so.

1.4.1 Controller Area Network

Controller Area Network (CAN) was primarily conceived for automotive applications to solve the cabling problems found in certain vehicles. However, because of its very reliable features and low-cost, it is also being considered in the automated manufacturing, process control environments (to interconnect intelligent devices such as modern sensors and actuators) and in building automation. Several attractive features in the CAN networks include the;

- Multimaster systems, i.e. bus access for every node is allowed if the bus is idle, also referred to as CSMA/CA or Carrier Sense Multiple Access
- Maximum data rates upto 1 Mbps
- Built-in mechanism for error detection and the localisation of error sources
There are four types of frames that can be transferred in a CAN network. Two of them are used during the normal operation of the CAN network: the Data Frame, which is used to transfer data from one station to another and the Remote Frame, which is used to request data from a distant station. The other two frames are used to signal an abnormal state of the CAN network namely the Error Frame which signals the existence of an error state and the Overload Frame which signals that a particular station is still not ready to transmit data.

Bus signals can have two different states: recessive bits (logic ‘1’) and dominant bits (logic ‘0’). The collision resolution mechanism works as follows: when the bus becomes idle (i.e.,) logic ‘1’, every station with pending messages will start to transmit. During the transmission of the identifier field, if a station transmitting a recessive bit reads a dominant bit, it means that there is a collision with at least one higher-priority message and consequently this station aborts the message transmission.

The highest priority message being transmitted will proceed without perceiving any collision, and thus will be successfully transmitted. The highest priority message is the one with most leading dominant bits on the identifier field. Obviously, each message stream must be uniquely identified. The station that lost the arbitration phase will automatically retry the transmission of its message.

1.4.2 Process Field Bus

Process Field (Profi) bus is a fieldbus standard for manufacturing automation and process control. The Profibus MAC protocol is based on a token passing procedure used by master stations to grant the bus access to each other, and a master slave procedure used by master stations to
communicate with slave stations. The token passing procedure uses a simplified version of the timed token protocol. This protocol, being based on the measurement of the token rotation time, induces a well-defined timing behaviour for the transferred messages, since the token cycle duration is upper-bounded. Therefore, it is able to support control-related traffic, with bounded response times.

1.4.3 Switched Ethernet

Ethernet has some attention because of its simplicity and wide acceptance. However, it has been known that Ethernet is not suitable for industrial networking because of its Medium Access Control (MAC), contention-based carrier sensing multiple access/collision detection, which exhibits unstable performance under heavy traffic and unbounded delay distribution. To overcome the limitation, Switched Ethernet is used which restricts the data collision within a port, allowing multiple data frames to be transferred simultaneously without data collision on the network.

1.4.4 Wireless Ethernet

Wireless Ethernet, based on the IEEE 802.11 standard, differs from wired Ethernet in MAC protocol. Unlike wired Ethernet nodes, wireless stations cannot “hear” a collision. A collision avoidance mechanism that is used, cannot entirely prevent collision and hence for each successful transmission, it sends acknowledgement message back to the original sender. At the same time, the theoretical data rate and practical throughput of a Wireless Ethernet should be considered. For example, raw data rates for 802.11 wireless networks range from 11 to 54 Mbps which is high when compared with wired and fieldbus communication. The use of wireless fieldbus or hybrid (wire/wireless) communication in NCS, helps to
interconnect many devices and reduces the cost and time needed for the installation and maintenance.

1.5 ISSUES IN NETWORK CONTROL SYSTEM

The insertion of the communication network in the feedback control loop makes the analysis and design of NCS complex. Conventional control theories with several standing assumptions, including synchronized control, non delayed sensing and actuation, must be reevaluated before they can be applied to NCS. The following are the important issues open for extensive research in NCS:

1.5.1 Network Induced Delays

During data exchange among devices connected to the shared medium, time-delays occur between sensor to controller $\tau_{sc}$ and between controller to actuator $\tau_{ca}$. Their sum $\tau_{in} = \tau_{sc} + \tau_{ca}$ represents the network induced delay. This delay, either constant (up to jitter) or time varying, can degrade the performance of control systems designed without considering the delay.

Network Induced Delay (NID) may vary widely according to the transmission time of messages and the overhead time. The transmission time through the media depends on the network protocols and the overhead time depends on the network scheduling method. NID can degrade the system’s performance and even cause system instability. The two inherent problems in NCS that results from network-induced delays are Message Rejection and Vacant Sampling.
Message Rejection: When two or more messages from the sensor reach the controller between two sampling instants, one of the messages will be discarded.

Vacant Sampling: When no data arrives to the controller during one sampling period, the controller can use the previous sample or an interpolated one.

![Network Induced Delay Diagram](image)

**Figure 1.2 Network Induced Delay**

1.5.2 Sampling Period

The performance of an NCS is highly dependent on the network sampling time. Increased network sampling time can improve the
performance of the system. Beyond a critical point, sampling frequency begins to adversely affect NCS’s performance because of network loading. When the number of messages is close to the network saturation limit, the message delivery time increases and may become unbounded. Optimizing the performance of an NCS can be achieved by balancing the increasing network sampling frequency with the resulting network performance degradation. While a shorter sampling period is preferable in most control systems, for some purposes it can be lengthened up to a certain bound within which stability of the system is guaranteed in spite of the performance degradation. This bound is called a Maximum Allowable Delay Bound (MADB).

A basic sampling period consists of sampling delay, transmission time of periodic data, transmission time of sporadic data, and transmission time of messages. The largest sampling period in an NCS depends on the largest MADB. In an NCS, a sampling period should be long enough to guarantee a real-time transmission of sporadic data and periodic data, also to enable minimum network utilization for a periodic data. However, the sampling period should be short in order to be within the MADB to guarantee the stability of the given system. Sometimes the sampling period may exceed the MADB because of network-induced delays.

Therefore, it is important to decrease the sampling period by minimizing network-induced delays. Due to the interaction of the network and control requirements, the selection of the best sampling period is a compromise. Smaller sampling periods guarantee a better control quality, but result in high frequency communication and may degrade the network quality. The degradation of network quality can further worsen the control quality due to longer time delays when the network traffic is nearly saturated. In general when the number of messages on the network increases, system nodes experience longer delays for sending and receiving information.
1.5.3 Jitter

Jitter is defined by IEEE as “Time-related, abrupt, spurious (false) variations in the duration of any specified related interval”, arises due to clock drift, branching in the code, scheduling, communication and use of certain computer hardware structure (e.g. cache memory). From the view of control, jitter is categorized as: control period jitter, delay jitter and sampling jitter. From the view of scheduling, jitter is categorized as: input jitter, output jitter, queuing jitter and deadline jitter. All kinds of jitter should be as small as possible to improve control performance. It is noted that vacant sampling and message rejection are harmful to all computer systems as also in control systems. Jitter degrades performance and causes instability even if for the case when vacant sampling or sample rejection does not occur. The jitter distorts a signal in a control system. The degradation depends very much on the dynamics of the process and on the type of jitter. The only way to get rid of delay jitter is to use a buffer, trading delay for jitter.

The sensor message will be transferred earlier in the cycle period, and in some other cycles it will be transferred later. The real time service provided by the control network will just guarantee that the sensor message will always be transferred before its deadline. The jitter problem can be even more acute, when the control network is shared between multiple control loops. In such case, a particular sensor requesting to transfer its data, may immediately transfer it or may have its request scheduled with other multiple requests (and thus, the transfer of the sensor data will be postponed). The Larger the number of messages requesting to be simultaneously transferred, the larger will be the induced jitter.
1.5.4 Data Packet Dropout

The network can be viewed as a web of unreliable data transmission paths. Some packets not only suffer from transmission delay but also may be lost during transmission in the worst case. Thus, how such packet dropouts affect the performance of an NCS is an issue that must be considered. Network packet drops, occasionally happen in NCS’s when there are node failures or message collisions.

Although most network protocols are equipped with retransmission mechanisms, they can only retransmit for a limited time. After this time has expired, the packets are dropped. Furthermore, for real-time feedback control data such as sensor measurements and calculated control signals, it may be advantageous to discard the old, non-transmitted message and transmit a new packet if it becomes available. In this way, the controller always receives fresh data for control calculation. Normally, feedback controlled plants can tolerate a certain amount of data loss. But it is important to determine, whether the system is stable, when to transmit the packets at a certain rate and required to compute acceptable lower bounds on the packet transmission rate.

1.6 REVIEW OF LITERATURE

The researches on performance improvement of NCS against the various issues such as those mentioned above are still in progress. The concepts and fundamental problems in NCS are discussed by many researchers and suggested different solutions to handle such issues. In this section the survey has been limited to main journal/conference publications, to provide comprehensive, representative and up-to-date projections of the research in this area.
Tipsuwan and Chow (2003) discuss the most recent developments in NCS. The paper summarizes many control system approaches for reducing the effect of delay, data packet loss, and necessity for using scheduling algorithm to avoid delay or loss of packet due to the communication network.

Shanbin Li et al (2002) explore the factors affecting the performance of NCS and necessity for development of control and computing strategies to improve NCS performance. Also modeling of NCS to analyse the delay is explained using Hidden Markov Model by assuming the states and their transient probability known in advance.

The merits and demerits of some research such as stochastic Lyapunov, state augmentation etc., for modeling and analyzing NCS with a linear plant-controller model with a randomly time-varying delay are discussed by Feng-Ge Wu et al (2002). This paper also provides future directions for improvement of NCS. Similarly, Yu jianyong et al (2004), Hokayem and Abdallah (2004) and Yang (2006) review the problems in NCS in different aspects and tremendous progress in control and computer methodologies adopted in many applications of NCS.

The communication network in the feedback of control system has been considered as a web of unreliable transmission paths, where in both real time and non-real time data are transmitted via either broadcast or point-to-point communication. The choice of communication network for NCS application is challenging and depends on parameters such as bandwidth, error checking and correction, protocol processing delay and so on. However, in NCS retransmitted data is considered as old information either to the controller or actuator, hence timely delivery of data is highly appreciated.
Middaugh (1992) introduces the fundamental characteristics of industrial networks and reviewed the characteristics and different network standards for typical applications. The paper claims the selection of network based on control engineers and nature of applications.

Lian et al (2001) evaluate the performance of different control networks such as Ethernet, ControlNet and DeviceNet under various conditions. The selection of the network is based on the requirements of the applications.

Myung-Kyun Kim et al (2004) analyzed the performance of the switched networks with the linear bus and the tree topologies with respect to the control cycle time, number of switches required and the required buffer size. From the results it is proved that linear bus topology is more advantageous than the tree topology.

Decotignie (2005) gives an overview of Ethernet from its first version to the new evolutions. The paper explains the limitations of the technology with regards to the requirements of industrial communication. With the evolution of the Internet toward higher QoS, particularly to support continuous media, voice, and images, the original 802.3 protocol has been enhanced and completed with new standards (priorities, switches, clock synchronization) that fill most of the requirements for an industrial solution.

Andreas Willig et al (2005) claim that the wireless technology can bring many benefits to industrial applications, one of them being the ability to reduce machine setup times by avoiding cabling. Wireless technologies have not gained widespread acceptance because of lack of acceptance and the difficulty in achieving the timely and successful transmission of packets over error-prone wireless channels. With the design of suitable protocol
mechanisms and transmission schemes, along with the careful combination of these schemes, important steps toward increasing the acceptance of wireless technologies for industrial applications can be made.

Kalogeras et al (2003) presented the parameters required for the achievement of hard and soft real-time traffic in the industrial environment and addressed the solution provided by three dominant technologies: WorldFIP, Profibus and Ethernet. The first two protocols have scheduling mechanisms that make possible the respect of real-time requirements while the seamless integration of IP traffic requires alterations in their protocol stack. The third is a best effort network protocol which may support hard real-time requirements either through the combination of its protocol and a protocol hearing real time characteristics, or through traffic limitations, or through network segmentation via switches.

The design problem of NCS with constant and random network delay in the forward and feedback channel was discussed by Guo-Ping Liu et al (2007). A novel networked predictive control scheme is proposed to overcome the effects of network delay and data dropout and it also provides an analytical stability criterion for closed-loop Networked Predictive Control (NPC) systems. In order to compensate for the network transmission delay, a network delay compensator in the channel from the controller to the actuator is proposed. The network delay compensator chooses the control value from the control latest prediction sequence.

Zhang et al (2007) propose a novel control scheme called the Guaranteed Cost Networked Control (GCNC) method for Takagi–Sugeno (T-S) fuzzy system with time delay, where the state feedback controller with GCNC using the T-S method is developed for NCS and its stability is established and validated through computer simulations.
The stability of model based NCS when the controller / actuator are updated with the sensor information at non-constant time intervals is given by Luis and Panos (2004). The controller uses an explicit model of the plant that approximates the plant dynamics and makes possible the stabilization of the plant even under slow network conditions.

Wang Yan et al (2005) discussed the robust controller design of nonlinear networked control systems with parametrical uncertainties. This is used to approximate the NCS in which NID is time varying and less than one sample period.

Nguyen Bao Kha and Kyoung Kwan Ahn (2006) presented a design of position control system by using self tuning fuzzy PID controller. The use of this control algorithm is to tune the parameters of the PID controller by integrating fuzzy inference and producing a fuzzy adaptive PID controller that can be used to improve the control performance of nonlinear systems.

Tipsuwan and Chow (1999) discuss about the method to implement a fuzzy logic speed controller for a DC motor. Heuristic knowledge is applied to define fuzzy membership functions and rules. The membership functions and rules are modified after initially borrowing the knowledge from a PI controller developed from a simple linear model. The hardware interface circuit and software algorithm are also described.

Zhang et al (2004) developed a fuzzy tuning scheme for PID controller for integrator plus time delay processes. A fuzzy rule base reasoning method is utilized on-line to determine a tuning parameter based on
the error and the first change of the error of the process. This tuning parameter is also used to calculate the PID controller parameters.

Wang et al (2005) investigated the robust stabilization problem for a class of sampled-data systems with nonlinear uncertainties. The controller and the plant are connected via network channel which may be subjected to data packet dropout and communication delays. Using the continuous-time model with delayed input, sufficient conditions on the robust stabilization is developed for NCS. The stabilizing feedback controllers produce a closed-loop system which is maximally tolerant to the uncertain nonlinear terms or is maximally tolerant to the delayed input.

Mahmoud and Abdulla (2003) provide a complete diagnostic profile of the role of delays in NCS. This paper analyzes the impact of delay sources on the stability and performance of NCS. An upper bound on the network delays using dynamic controllers is also developed.

Zhigang Sun et al (2004) have modeled and studied the Networked Control System with multiple packet transmission and stability of the Multi-Input Multi-Output system with transmission delays.

Lian et al (2001 and 2002) discuss the impact of network architecture on control performance in NCS providing design consideration related to control quality of performance as well as network quality of service. This paper identifies several key components of the time delay through an analysis of network protocols and control dynamics.

Feng-Li Lian et al (2003 and 2006) discuss the utilization of communication resources in NCS and the requirement of control measures to be taken to avoid data latency and communication overhead. The performance
of information sharing of multiple cooperative agents over one communication network and design methodologies of guaranteeing acceptable control and communication performance in a networked control system are dealt.

Manel Velasco et al (2004) and Al-Hammouril et al (2006) presents a scheme for bandwidth allocation in networked control systems (NCS), which targets NCS working over large distributed networks. Ensuring the stability of each NCS, the scheme allocates the bandwidth to maximize the performance of all NCS.

Dawn Tilbury et al (2002) describes a new framework for distributed control systems in which estimators are used at each node to estimate the values of the outputs at the other nodes using which significant savings required in bandwidth is achieved.

Wei Zhang (2001) has discussed network issues such as bandwidth, quantization, survivability, reliability and message delay with control system issues like stability, performance and fault tolerance.

Zhang et al (2001) have analyzed several fundamental issues in the network control system like network induced delay and multiple packet transmission, jitter, time triggered and event-triggered schemes.

Branicky et al (2000 and 2002) have discussed the conventional control theories and several fundamental issues like network induced delay, stability and calculation methods of allowable delay for the stability analysis of NCS.
Martin Andersson et al (2005) have developed TRUETIME, a toolbox for simulation of distributed real-time control systems. TRUETIME makes it possible to simulate the timely behaviour of real-time kernels executing controller tasks. The toolbox also makes it possible to simulate models of network protocols and their influence on networked control loops.

Manel Velasco et al (2005) have presented a stability test that permits to assess the stability of a closed loop system whose control loops operations are subject to bounded varying sampling rates and time delays.

Otanez et al (2002) have discussed the effective way of improving the networked control systems performance by reducing the network traffic. Adjustable dead bands are explored as a solution to reduce the network traffic.

Walsh et al (2001) have considered a continuous plant and a continuous controller and introduced the notation of maximum allowable transfer interval and try once discard scheduling method.

Hong seong park et al (2002) has presented a scheduling algorithm that can allocate the bandwidth of a network and determine sensor data sampling periods. As a basic parameter for the scheduling, MADB is used, which guarantees the stability of NCS and is derived from the characteristics of the plant.

Hong and Kim (2000) have proposed a bandwidth allocation scheme that is applicable to the CAN Protocol. The bandwidth allocation scheme investigated in this study is based on the pre run time scheduling.
Hong (1995) has developed a scheduling algorithm for determining data sampling time using the window concept and analyzed the performance requirement of control loops. Performances of feedback control loops are directly dependent on the loop delay.

Tao bai Zhiming Wu et al (2005) have analyzed the network induced delay and jitter, affecting the performance of the NCS. They have studied the relationships of the sampling periods of the control loops, network induced delay and jitter and proposed an algorithm of jitter dependent optimal bandwidth scheduling based on the idea of multi-cycles scheduling.

Youxian Sun (2005) has examined the problem of network scheduling in a NCS that consists of multiple control loops and proposed network scheduler that integrates feedback control with real time scheduling.

Cuneyt Bayilmis et al (2005) have designed a Wireless Interfacing Unit (WIU) that achieves interconnection of two CAN2.0A segments using an IEEE 802.11b WLAN. The introduction of the WIU induces a delay and from the simulation results they have proved that the system performance meets the requirements of Society of Automation Engineers (SAE) Bench mark.

Ismail Erturk (2002) discusses about the use of CAN network in a Traffic control system with a central management unit over Wireless Asynchronous Transfer mode (WATM). It also explains the encapsulation of the CAN frame into the WATM frame for inter networking between the two systems.

Suk Lee et al (2002) focus on protocol conversion function from Profibus format to the IEEE 802.11(WLAN) format and it also confirms the
feasibility of deployment of such hybrid networks by analyzing the data latency and throughput.

Kutlu et al (1996) present the performance analysis of the Wireless Medium Access Control (WMAC) protocol and the Remote Frame Medium Access Control (RFMAC) for distributed and wireless communication respectively. The simulation results show that the low priority messages are not delivered properly at lower speeds but even then these can be employed at higher speeds.

Bechir BenGouissem et al (2006) use wireless CAN protocol for data centric communication model. In industrial sensor networks to manage concurrency among the nodes priority is assigned to the data.

Bernstein (2001) explained the concepts that quantify sensor performance specifications. The Hammerstein-Wiener nonlinear feedback model which involves a linear dynamic block surrounded by three static nonlinear blocks is discussed. The static and dynamic response of a sensor is analysed and also the mechanism for calibrating the sensor is discussed.

Massieh Najafi et al (2002) developed Auto-Associative Neural Networks (AANNs) for single sensor fault detection. Finding the difference between the input and output of the AANN is useful in determining sensor problems but is not sufficient to localize the faulty sensors because of the inherent nonlinearity of the AANN and the non-orthogonal nature of the inputs. An extension to the AANN concept has been developed to locate single faulty sensors in synthetic data and also to reproduce the real value of the faulty sensor output. The single sensor fault can be detected and corrected up to 15% noisy situation, beyond which the performance of AANN decreases.
Alex Nugent et al (2002) exploited the dynamics of unsupervised online learning rules for fault tolerance in neural network classifiers. Radial Basis Function (RBF) neural network is used to solve two class classification problems to implement a form of self-organized fault tolerance. First, in the design stage the supervised learning is used to find a good set of network weights and then in online stage the static network weights are replaced by the dynamic update mechanism. When the network is subjected to fault it is retrained to adjust the weights. Incremental dynamic faults are introduced according to a linear schedule and the maximum error rate of 0.3 is obtained. The performance of retraining will depend on how often the faults occur and how often the retraining can occur.

Nasuti and Napolitano (2000) presented an on-line learning approach for the problem of sensor failure detection, identification, and accommodation using neural networks. A modified version of Gaussian Radial Basis Function network (GRBF) is used to approximate the unknown nonlinearities of the dynamic system. Two identical linear filters are employed to obtain the error output and the residual from the estimated derivative of the sensor measurement. During the first part of the simulation the Sensor Failure Detection, Identification and Accommodation (SFDIA) scheme gradually learns the system dynamics and the residual decreases. When the sensor fails, the GRBF provides a good estimation of the true value of the variable, assuming that the learning is slow enough to prevent a quick adaptation to the faulty signal.

Roman Ilin et al (2007) have shown that Cellular Simultaneous Recurrent Neural Network is more powerful function approximator than Multi Layer Perceptrons. The speed of convergence has been improved by training the network with Extended Kalman Filter.
Jorge Henriques et al (1999) presented a modified recurrent Elman network as general tool for modeling real time heating systems together with a truncated backpropagation algorithm for training. The Elman network with ‘n’ hidden units represent an \( n^{th} \) order dynamic system, therefore it can be used to model the nonlinear system efficiently. The simulation result shows that the neural model is intimately dependent on the data set used for learning and can be applied for prediction in the same condition of the training set.

Younghwan An (1998) focused on the performance of a Neural Network (NN) based fault tolerant system within a flight control system. This fault tolerant flight control system integrates sensor and actuator failure detection, identification, and accommodation (SFDIA and AFDIA). The SFDIA task is achieved by incorporating a Main Neural Network (MNN) and a set of ‘n’ Decentralized Neural Network (DNN) for a system with ‘n’ sensors. The NN’s are trained on-line, using the Extended Back-Propagation Algorithm (EBPA). The purpose of the MNN is to detect a wide variety of sensor failures while the purpose of the DNN is to identify the particular sensor that has failed and accommodate the failure.

Silvestri et al (1994) presented an NN approach for SFDIA, without any sensor redundancy. Online learning of NN is performed by using EBPA and the goal is to enhance the capability of each neuron in the hidden and output layers. This is done by introducing a modified activation function which includes upper and lower bounds of the output of a generic neuron of both hidden and output layer respectively. During the on-line training, the difference between the sensor output and the network output is used by the EBPA to update the NN. As the learning process continues, NN provides better estimate until the error threshold is reached.
Moustapha and Selmic (2008) presented sensor node identification and fault detection using Recurrent Neural Network (RNN) based on standard back propagation training for wireless sensor network. RNNs are used to model a sensor node, its dynamics, and interconnections with other sensor nodes. Each sensor is modeled as a Hammerstein-Wienner nonlinear feedback dynamic sensor and its output is given to RNN. The input to the RNN sensor model is the present and past output of neighboring sensor node and its delayed output. The communications link uncertainties are represented by confidence factors \( c_{ij} < 1 \), where \( i \neq j \) represents the node number.

Gallman and Narendra (1976) presented a new model for identifying nonlinear systems called Uryson model. The multipath structure, with each path consisting of a polynomial followed by linear dynamics, is a direct extension of the single path Hammerstein model. An iterative algorithm for obtaining the dynamics from finite length input and noisy output data records is presented. The Uryson model consists of several Hammerstein models in parallel, each path having the same input and with the several outputs summed. Orthonormal Hermite polynomial is selected and performs direct minimization of the integrated squared error between plant output and model output using iterative identification algorithm for finite observation time.

Zhirabok and Preobragenskaya (1993) dealt with the problem of Instrument (sensor) Fault Detection and Isolation (IFDI) based on analytical redundancy where the nonlinear models of the actual systems were used. The IFDI process is provided by the bank of the nonlinear observers. The most unreliable units of automatic systems are sensors as usual. A fault is understood as any kind of malfunction in the sensor. It is proposed that different sensors may contain a common unit, hence the single fault may distort a few of the outputs.
Straub and Shroder (1996) presented an approach for identifying faults in a nonlinear dynamic system. It is based on the use of a General Regression Neural Network (GRNN), the parameters of which are trained by the Extended Kalman Filter Method. General on-line methods for identification using NN are proposed, both for full-state measurement and for reduced-state-measurement. Methods have been presented to identify nonlinearity with one measured state of the system. These identification methods are based on the adaptation of the NN using the so-called error models.

Ahmed (2001) presented the application of rapid NN for system identification of unknown nonlinear dynamic systems when the inputs and outputs are accessible for measurements. The learning algorithm of the rapid NN does not need iterative procedure. NN can be viewed as the nonlinear dynamic mapping of control input onto observation outputs. There are two identification structures: parallel structure and series-parallel structure. In parallel structure, the neural network and the system receives the same inputs. The outputs of the system are not used as inputs to the network. In series-parallel structure, the neural network and the system receive the same input as in parallel structure, but the output of the system is feedback to the network as the input.

Perhinschi et al (2006) developed an adaptive threshold approach for the design of an actuator failure detection and identification. This method maximizes failure detectability while minimizing false alarm rates. It reduces the delays associated with the constant threshold method. The floating limiter concept is used to compute variable thresholds for the parameters involved in the AFDI process.
1.7 OBJECTIVE AND SCOPE OF THE WORK

Most of the existing literature aim to provide the control system analysis and design, which is analytical. In this work, stability analysis for various cases is done for reducing the effect of NID and communication bandwidth. The methods to reduce the presence of NID and limited communication bandwidth are investigated from control and embedded perspective which is simpler among the approaches adopted to handle the issues in NCS.

The scope of this thesis is limited to the following objective:

- A fuzzy based compensator is suggested to reduce the effect of NID.
- The use of local estimators in Multi-Input Multi-output (MIMO) system is suggested to reduce the frequency of data transfer over a network.
- Exploring the use of different types of scheduling algorithm in NCS, the report formulates a dynamic scheduling algorithm to reduce the delay and communication overhead.
- A Hybrid NCS which uses both wired and wireless communication medium is suggested to handle large volume of data packets and also to maintain a constant delay among all the nodes.
- A neural network based sensor model is suggested for the sensor fault detection.
1.8 OUTLINE OF THE THESIS

The thesis is organized into five chapters and chapter wise summaries stating the development and results obtained from investigations presented in the sections that follow.

Chapter 2 is concerned with the control approach for reducing the effect of NID and methods for communication bandwidth reduction. This chapter elaborates the need for fuzzy based compensator to overcome the effect of NID and suggests the use of local estimators in a MIMO system to reduce the communication bandwidth.

In Chapter 3, the embedded approach for reducing both the delay and communication bandwidth reduction is discussed by suggesting a dynamic scheduling algorithm. A simple control system is considered as a case study to analyse the need for using dynamic scheduling algorithm. Also the scope for incorporating the benefits of wireless network in NCS application, by modeling a hybrid wired/wireless communication without affecting the stability.

A design of fault tolerant NCS architecture to improve the stability of the system by avoiding the transmission of faulty data over the communication network is the scope of chapter 4. A fully connected recurrent neural network based sensor modeling is discussed. The performance of two different learning methods for neural network in fault identification process is also discussed.

The summary of the contributions of this thesis and future direction of research in NCS are discussed in Chapter 5.