CHAPTER 2

NETWORKED CONTROL SYSTEMS

This chapter gives an overview of the networked control systems and their operation in two different modes. The challenges faced in the networked control systems are discussed. The related research works is also reviewed in this chapter. The DC motor is modeled and the networked DC motor is discussed from control design point of view.

2.1 OVERVIEW ON NETWORKED CONTROL SYSTEMS

A Networked Control Systems refers to a control system whose feedback loop is closed through some network channels. NCS contain a large number of interconnected devices that exchange data through communication networks which includes office and home automation, building automation, intelligent vehicle systems, industrial automation, and advanced spacecraft and aircraft.

Networked control systems provides several advantages such as modular and flexible system design, simple and fast implementation, powerful system diagnosis, maintenance utilities, reduce the complexity in wiring connection and the costs of medias. Because of these attractive benefits research and development in several network protocols for various applications have been released. Especially the research has extended in the area of industrial control through networks. For example, Controller Area Network (CAN) was originally developed in 1983 by German company
Robert Bosch for use in car industries and also used in many industrial control applications.

Profibus is another network developed by German’s in 1987 which is a broadcast bus protocol that operates as a multi master/slave system. Many other industrial network protocols including device net and foundation fieldbus were also developed about the same time period. Most of these protocols are typically robust and reliable for real time control purpose.

Meanwhile, the technologies on general computer networks especially Ethernet have also progressed very rapidly. With the increasing speed, decreasing price, numerous software and application, and well established infrastructure, these networks became major competitors to the industrial networks for control applications.

Furthermore, the internet popularity has brought these networks into various organizations. Thus the control applications can utilize these networks to connect to the internet in order to perform remote control at much farther distance than in the past without investing on the whole infrastructure.

Although the industrial networks have been enhanced for internet connectivity, the widespread usages and cheaper price of the general networks are still attractive for use in control applications. Many different networks have been promoted as control networks. However the strict timing requirements that closed-loop pose on the distributed implementations call for networks able to provide real time guarantees, such as field buses.

Real-time guarantees provided by networks refers to the fact that the data exchanged over the communication media must be received and sent with a bounded time interval, else a timing fault is said to occur. Therefore,
for control systems the control networks must meet two main criteria as bounded time delay and guaranteed transmission. The unsuccessful transmitted or large and unpredicted time-delayed messages may deteriorate the control system performance, even causing a critical failure in the system.

Network delays may not significantly affect an open loop control system such as on-off relay systems in industrial plants. However, the open loop control configuration may not be appropriate and adequate for time sensitive high performance control applications. These applications require feedback data sent across the network in order to correct the output error. Therefore an advanced methodology is required to handle network delays and losses in a closed loop control system over a network.

Networked control systems are distributed real time control systems consisting of the plant, sensors, controllers, actuators and a shared data network that is used for transferring data between the components of the system. A general NCS layout is shown in Figure 2.1. To perform closed loop networked control operations, a controller needs to send control data to a system plant, and receive feedback data from the plant through a communication network to update control data.

The major drawback of networked control systems is that the dynamics of network affect the control system stability due to the network induced delay, losses of signals and disturbance.
In order to study, analyze and design the controller for the NCS, the networked dc motor control is considered in this thesis. The DC motors have been widely utilized in many industrial for control applications as a robotic manipulator, a conveyor belt, or a computer numerical machine. Thus a DC motor system will be used to illustrate the concepts and challenges in NCS. The speed of the remote DC motor has to be controlled through the network from server or central unit. Hence the data network transfers control data from controller to plant (remote DC motor) and feedback signal (speed) data from remote sensor to controller.

2.2 A SURVEY ON NETWORKED CONTROL SYSTEMS

Allaoua et al (2009) designed a PID-PSO controller for the speed control of DC motor drive by determining the optimal PID controller parameters using the PSO technique. In this, the authors showed that the proposed controller can perform an efficient search for the optimal PID controller parameters with robustness as no overshoot, minimal rise time and zero steady state error than comparing with Fuzzy-PSO controller.
Almutairi and Chow (2002) proposed the full adaptive fuzzy modulation where both consequent parameters and membership functions parameters in the antecedent part are tuned adaptively for the IP network-induced time delays in IP networked PI control system. The authors illustrated the proposed scheme using networked based dc motor control and compared the results with two tuning methods as directly tuned PI parameters and partial adaptive fuzzy modulation.

Almutairi and Chow (2002a) presented a partial adaptation fuzzy modulation scheme where the consequent parameters in the fuzzy rules are tuned adaptively and the membership functions parameters in the antecedent are fixed. The authors illustrated the effectiveness of the proposed scheme over a direct PI controller parameter tuning by using a network-based controlled DC motor.

Almutairi et al (2001) proposed the use of the fuzzy logic concept to modulate the system control gain of the PI controller for compensating the time delay problems in the network based controlled DC motor. For the compensation and improvement in the performance of the PI control under difference network delays and bandwidth, the author has introduced a parameter which is a nonlinear function that discrete the input/output relation of the fuzzy compensator to the existing PI controllers control signal such that new control signal will be provided by the central controller.

Branicky et al (2000) modeled and studied a networked control systems model containing a clock-driven sensors, event-driven controller and actuator. The author compared the timing of this model with model with a clock-driven controller and analyzed the relationship between the sampling
rate and network induced delay using stability region plot, and characterized using hybrid systems technique.

Cao and Zhang (2006) presented the fuzzy PID controller in dealing with random delays in NCS due to its flexibility and adaptation in uncertain elements.

Caruntu and Lazar (2012) proposed an one-step ahead model predictive control strategy, that can handle the performance, physical constraints and explicitly take into account the bounds of the disturbances caused by the time varying delays. Caruntu also employed lyapunov function to obtain stability guarantee for the proposed one-step ahead model predictive control scheme.

Chow and Tipsuwan (2003) proposed a novel approach for networked DC motor control system using PID controller gain adaptation to compensate the changes in network Quality of Service requirement.


The quadratic Lyapunov function has been used by Dong et al (2009) to design $H_\infty$ fuzzy controllers such that, for the admissible random measurement missing and repeated scalar nonlinearities, the closed-loop T-S fuzzy system is stochastically stable and preserves a guaranteed $H_\infty$ performance.
Gaing (2004) used PSO algorithm for determining the PID controller parameters. The effectiveness of PSO-PID controller is verified by using in an Automatic Voltage Regulator (AVR) system and compared with genetic algorithm.

Gao and Chen (2007) solved the problem of robust $H\infty$ estimation for linear systems with polytopic uncertain parameters and subject to limited communication capacity as signal transmission delay, measurement quantization and data packet dropout in the typical network environment. A LMI based conditions was formulated by the authors for the existence of admissible filter which ensured the filtering error systems to be asymptotically stable with the prescribed $H\infty$ disturbance attenuation level. The authors illustrated the applicability and effectiveness of the filter design methodology using examples of mass-spring systems.

Gao et al (2009) used Takagi-Sugeno fuzzy model to model the nonlinear plant, and the communication link failure was modeled via a stochastic variable satisfying the Bernoulli random binary distribution.

Goodwin et al (2004) employed moving horizon techniques to deal with both the measurement and control quantization issues for multivariable plants where the actuator, controller and sensors are connected via a data-rate limited digital communications channel. The authors imposed a communication constraint in order to minimize bandwidth utilization which restricts all transmitted data to belong to a finite set and only permits one plant to be addressed at a time and also illustrated the methodology by simulations and a laboratory-based pilot-scale study.
Gunasekaran and Potluri (2007) explains point to point architecture of control system SCADA and DCS network and developed a feedback controller for the networked control system to face the network delays, packet losses and limited bandwidth.

Heemels et al (2010) presented a new model for networked control systems which involves varying transmission intervals, varying transmission delays and communication constraints. Based on the model the authors provided a lyapunov-based characterization of stability and obtained explicit bound on the maximum allowable transmission interval and the maximum allowable delay which guarantee stability of networked control systems.

Hespanha et al (2007) reviewed several recent results on estimation, analysis, and controller synthesis for networked control systems and surveyed address channel limitations in terms of packet-rates, sampling, network delay, and packet dropouts.

Jia et al (2009) designed a Takagi-Sugeno based fuzzy model and designed a controller with prescribed $H\infty$ tracking performance by lyapunov stability theory for networked control system considering network-induced delay and packet losses in transmission path.

Kim et al (2003) proposes a method to obtain a maximum allowable delay bound for a scheduling of networked control systems in terms of linear matrix inequalities and which can give a much less conservative delay bound than the existing methods. Through the proposed method a network scheduling method is presented by the authors based on the delay obtained and then the bandwidth of a network is allocated to each node, the sampling period of each sensor and controller is determined. They also proved
that this method can handle three data types as sporadic data, periodic data, and message and then guarantees real-time transmission of sporadic and periodic data, and minimum network utilization for non-real time message.

Krstic (2010) constructed a time varying lyapunov function and established exponential stability for linear time-invariant systems with a time-varying input delay. For the case of time varying sensor delay the author also developed an observer equivalent of the predictor feedback design.

Lee (1990) presented a survey of the Fuzzy Logic Controller and discussed on the general methodology for constructing fuzzy logic controller, fuzzification and defuzzification strategies, fuzzy implication, derivation of the database and fuzzy control rules and analysis of fuzzy reasoning mechanisms.

Lee and Lee (2002) implemented networked control system via Profibus-DP network for DC motor speed control for the performance evaluation. They modified the two conventional and traditionally used Ziegler–Nichols and Cohen Coon tuning methods for PID controller in order to minimize the effects of network delays on the system.

Lee et al (2003) focused on the application of fuzzy logic control for NCS and verified the approach on NCS for servo motor control via a Profibus-DP network. They also analyzed the network induced delay to find the cause of the delay and compared the effectiveness of fuzzy logic controller’s performance with conventional PID and Ziegler-Nichols tuned PID controllers.
Li et al (2009) presented an Estimation of Distribution Algorithm (EDA) based Memoryless State Feedback Control (MSFC) called E_MSFC an output tracking controller method for networked DC motor system with time delays and packet losses where both system stability and control performance are considered during the controller design stage and can be easily implemented to various applications due to its simple structure.

Two discrete-time models are proposed by introducing lifting technique with the construction of two predictive observer controllers and the output feedback stabilization problem for a class of networked control system under network-induced delay and data losses was investigated by Li et al (2008). They also derived the stability conditions of NCS via network-condition-dependent lyapunov function and based on the stability conditions the corresponding controller design problems were addressed.

Li et al (2012) investigated the stabilization problem for NCS with random time delays and constructed a novel networked controller with delay-dependent control gains. The corresponding stability conditions, as well as controller design approaches are also provided.

Li and Baillieul (2004) considered a scalar model of digital finite communication bandwidth (DFCB) control in NCS that accommodates time-varying data-rate constraints and designed a feedback control designs with different number of quantization levels that tolerate constrained data-rates differently on feedback loops which leads to the binary control.

Networked control systems with constant and random network delay in the forward and feedback channels, respectively, is considered by Liu et al (2007) and proposed novel Networked Predictive Control (NPC) scheme
to overcome the effects of network delay and data dropout. They presented stability criteria of closed-loop NPC systems and also explained the necessary and sufficient conditions for the stability of closed-loop NCS with constant time delay.

Liu et al (2010) analyzed the stability problem of continuous time positive systems with time varying delays. The author proved that such a system is asymptotically stable for any continuous bounded delay if and only if the sum of all the system matrices is a Hurwitz matrix and this result is a time varying version of the widely known asymptotic stability criterion for constant delay positive systems.

Luo and Chen (2000) reviewed and proposed behavior-programming event-driven control concept to avoid disturbances of the internet latency i.e. the unpredicted transmission delay of the network for networked mobile robot systems. The authors grouped primitive local intelligence of the mobile robot into motion assistant, motion planner and motion executor, where each of a group is treated as an agent and integrated them based on multi-agent concept, communicated through a centralized control architecture.

Montestruque and Antsaklis (2004) studied the stability of model based-networked control systems when the controller/actuator is updated with the sensor information at non-constant time intervals. They derived sufficient conditions for lyapunov stability and studied networked control systems with transmission times that are varying either within a time interval or are driven by a stochastic process with identical independent distributed and Markov-chain.
Mu et al (2009) proposed a modified PSO based on simulated annealing algorithm.

Nagaraj et al (2008) compared intelligent tuning techniques (evolutionary programming, genetic algorithm, and PSO technique) with conventional methods (continuous cycling method and Ziegler-Nichols method) for tuning the parameters of PID controllers. The authors proved that the intelligent technique provides better results by illustrating the armature dc motor control.

Nasri et al (2007) presented a Particle Swarm Optimization (PSO) method for determining the optimal PID controller parameters for speed control of a linear brushless DC motor. The author proved the efficiency of PSO technique for PID parameters search in improving the step response characteristics by comparing it with Genetic Algorithm and Linear Quadratic Regulator.

Nesic and Teel (2004) presented the results on input–output stability of networked control systems for a large class of (static protocols and dynamical protocol called try-once-discard) network scheduling protocols which provides an unifying framework for generating new scheduling protocols that preserve stability properties of the system if a design parameter is chosen sufficiently small that can be used to treat NCS with data packet dropouts.

Niu and Ho (2010) investigated the design of sliding mode control subjected to packet loss in feedback loop of the communication network and proposed an estimation method to compensate the packet dropout. They also
introduced a discrete time integral sliding surface involving dropout probability and designed a sliding mode controller.

Bacterial foraging technique was adapted by Oyekan and Hu (2010) to guide the search on the optimal parameters of PID controller in the parameters search space for automatic tuning of a PID controller for a unmanned aerial vehicles.

Pang and Liu (2012) presented a secure networked predictive control architecture by integrating the data encryption standard algorithm, message digest algorithm, time stamp strategy and the recursion networked predictive control method for data confidentiality service, detection and compensation of deception attacks which has been treated as the network round trip time delay.

Paul and Hector (2009) obtained a fuzzy Takagi-Sugeno model through input-output data for a dynamic nonlinear multiple input multiple output systems and using this fuzzy model a supervisory fuzzy control was designed to minimize the effects caused by the time delay due to network communication.

Ren et al (2009) developed the controller for the speed control of induction motors by introducing networked control systems (NCSs) into the induction motor driving system with the network time delay occurs in the transport medium of network data. They used a feedback linearization method to achieve input-output linearization and decoupling control of the induction motor driving system based on rotor flux model, and then analyzed the characteristic of network data in terms of the inherent network time delay.
Seiler and Sengupta (2005) studied the effect of a network in the feedback loop of the control system by using a stochastic packet loss model for the network. The authors computed a $H_\infty$ norm via a necessary and sufficient matrix inequality condition and then using the norm $H_\infty$ the performance of the system is measured. Also they derived the necessary and sufficient linear matrix inequality conditions for the synthesis of the $H_\infty$ optimal controller for a discrete-time jump system.

Tabbara and Nesic (2008) introduced a new definition of stochastic protocols for networked control system and the stochastic analog of the notion of uniform persistency of excitation of protocols which is applied directly to common wireless and wireline networked control systems, including those built on carrier-sense multiple access style protocols with Ethernet. The authors have also presented conditions for a general class of non-linear networked control systems with exogenous disturbances using stochastic protocols in the presence of random packet transmission times, collisions and packet dropouts that are sufficient for stability from exogenous disturbance to NCS slate with a linear finite expected gain.

Tabbara et al (2007) proposed a general framework for analyzing the stability of general nonlinear networked control systems with disturbances in the setting of stability and provides sharp bounds for the maximum allowable transfer interval of the scheduling protocols than previous property of uniform persistent exciting scheduling protocols. The authors also provided a proof for the qualitative statement for high enough transmission rates, a scheduling protocol that regularly visits every NCS node within a fixed period of time ought to preserve stability properties of the network-free system.
Tian et al (2007) designed a self tuning fuzzy controller for a NCS with first level of controller to control the plant directly and second level controllers to adjust the quantification and the scaling factors of the first-level fuzzy controller in an online and adaptive way according to the system error and the change of the error.

Tipsuwan and Chow (2003) presented an overview on NCS structure and described network delays characteristics and their effects on the system. They surveyed on the control methodologies for networked control systems facing network induced delays which includes augmented deterministic discrete time model methodology, queuing method, optimal stochastic control method, perturbation method, sampling time scheduling method, robust control method, fuzzy logic modulation, event based method and end user control adaptation method for a closed loop control system over a data network with different applications.

Tipsuwan and Chow (2004) used a gain scheduling approach with respect to the current network traffic condition to enhance widely used and existing PI controllers for using over IP networks. The author also proved the chances to apply the proposed gain scheduling scheme for a networked PI controller on actual IP network environment with reasonably long round-trip time delays and relatively low variations using simulation.

Wang et al (2010) considered the networked synchronization control problem for the coupled dynamic networks with time varying delay and constructed a new closed loop dynamic error system with markovian jump parameters. The authors using kronecker product and the stochastic lyapunov stability theory, a delay depended stochastic stability criterion for the closed loop coupled dynamic error system has been derived in terms of linear matrix inequality which guarantees that the coupled dynamic network systems are stochastically synchronized.

Wang et al (2007) designed an observer based feedback controller in the presence of random packet losses to stabilize the networked system in the sense of mean square and also achieved the prescribed \( H_{\infty} \) disturbance-rejection-attenuation level. Both the stability-analysis and controller-synthesis problems have been investigated and the author also showed that the controller design problem can be solvable by making LMI feasible.

Wen and Geng (2012) studied distributed networked control system and used the input – output method for obtaining a stability result which can be used to analyze the network with heterogeneous subsystems and non-ideal data links where the non-idealizations in the network are network induced delays and the static non-linearities.

Witheephanich et al (2005) proposed the graphical loop shaping technique for designing the robust controller to compensate the uncertain delays in the NCS. Then, the Robust Nominal Model Following Control (RNMFC) scheme is designed to handle the plant uncertainties and illustrated the benefits of the scheme with network-based speed control of dc motor.
Yang et al (2007) designed the robust $H_\infty$ controller with feasible linear matrix inequalities which guarantees the asymptotically mean-square stable. They also proved that the controlled output stabilizes the $H_\infty$ performance constraint, for all admissible parameter uncertainties and all possible missing observations.

Yue et al (2004) designed a controller based on a delay-dependent approach for the networked control system under consideration of both the network-induced delay and the data dropout in the transmission. The authors solved a set of linear matrix inequalities and derived the feedback gain of a memoryless controller and the maximum allowable value of the network-induced delay.

Yue et al (2005) proposed a new analysis method for $H_\infty$ performance of networked control systems by introducing and employing some slack matrix variables the information of the lower bound of the network-induced delay. The authors designed $H_\infty$ controller which can be obtained by solving a set of linear matrix inequalities as memoryless type.

Yue et al (2009) investigated the stabilization problem for a class of linear systems with stochastic input delay and proposed a new model based on the information of probability-distribution of the time delay, which dependent parameter matrices. The authors solved a set of LMIs for the stability and stabilization of the system in the new model.

Zamani et al (2009) proposed particle swarm optimization algorithm to design a $H_\infty$ PID controller with robust stability and disturbance attenuation for single input single output flexible link manipulator and a multiple input and multiple output super maneuverable F18/HARV fighter
aircraft system. They also verified and proved the superiority of the performance of the PSO based method for these applications than existing genetic based methods for $H_{\infty}$ PID controllers.

Zhang et al (2009) designed a fuzzy estimator to estimate the states of a nonlinear NCS plant via limited sampling information considering both network-induced delay and packet losses in a uniform framework.

Zhang and Yu (2010) studied the stabilization problem for sampled data control systems with control inputs missing and derived the sufficient condition for the existence of exponentially stabilizing state feedback controllers via the switched system approach.

Zheng et al (2006) used Takagi-Sugeno (T-S) based fuzzy model for networked control systems since this method does not require the knowledge of the exact values of network-induced delays and also handles the data loss.

Zeigler and Nichols (1942) presented the tuning methodology and provided the formulas for finding the parameters for three basic controllers as Proportional, Proportional-Integral and Proportional-Integral-Derivative.

From the survey of the previous existing methods it has been observed that many authors have given methodologies which possess many computational algorithms, mathematical calculations and theorems. It makes the industrial environment difficult in terms of practical implementation. Thus, various intelligent controllers such as fuzzy modulated PID, fuzzy logic, neural, Neuro-Fuzzy and PID-PSO are proposed for the networked DC motor control.
2.3 DIFFERENT APPROACHES OF NCS

According to the concept of NCS by Chow and Tipsuwan (2003) there are two approaches to utilize a data network for control of DC motor as Direct Structure and Hierarchical Structure.

In the hierarchical approach, each DC motor has its own controller. The controller and the DC motor are physically located close to each other. This controller receives a desired set point remotely from the central controller through the network, and then uses the given set point to perform closed loop control locally as shown in Figure 2.2. The status or the sensor measurement of the DC motor is sent back to the central controller via the network. The approach provides modularity for each DC motor system. Each system is easy to be reconfigured. However, the major drawback of this approach is poor interaction between the main central controller and each DC motor controller.

![Figure 2.2 Hierarchical structure configuration of NCS](image)

M: Motor  
S: Sensor  
CC: Central Controller  
C: Remote Controller
On the other hand, as shown in Figure 2.3 the direct structure approach uses a network as a medium to directly transfer control signals and sensor measurements between a DC motor and a controller. The closed loop control of the DC motor is communicated over the network. Each DC motor in this case is attached to a simple interface unit. This unit converts the data from the controller to an actual control signal and the sensor measurement to a data frame for sending back to the controller. In fact this interface can also be thought of as a simple remote controller. Systems formulated by this approach are so called network-based or networked control systems which can provide better interaction and highly flexibility for controlling DC motor.

The direct structure configuration is considered in the thesis for discussing the challenges in networked DC motor control.

**Figure 2.3 Direct structure configuration of NCS**
2.4 NCS INHERENT ISSUES

2.4.1 Packet Loss

Due to several factors such as transmission time outs, transmission errors and limited buffer size the data packet loss is an inherent problem with most computer networks. The transmission protocols are implemented with various error detection and correction schemes such as parity bit, cyclic redundancy check and frame checksum to handle the loss without correcting an error, indicating that a data has an error. Then the mentioned methods might fail and hence the data are deemed lost. And also with this some of the data get lost in the network due to inferences, noise, node failure and packet collision.

A lost data is either retransmitted or not, depending on the protocols used. There are two types of transmission as single-packet and multiple-packet transmission. In a single-packet transmission the sensor or actuator data are sent together into one network packet at the same time for transmission, whereas in multiple-packet the sensor or actuator data use separate network packets for transmission. The single-packet transmission can only carry limited information hence multiple-packet transmission is used widely. Also the sensor and actuators in an NCS are often distributed over a large area and hence it is impossible to transmit all the data into one network.

Now when the multiple-packet is used to deliver the plant output and control inputs at the same moment for a NCS, is not true always due to network-access delays and packet dropouts. Hence the controllers control signal calculation update becomes a problem. Normally when feedback controlled plants are used a certain amount of data loss are tolerated but it is valuable to determine whether the system is stable before the packets are transmitted at a certain transmission rate.
2.4.2 Delay Analysis

The next major problem in NCS is that the network introduces random, possibly unbounded delays. The network-induced delays in networked control systems occur when actuators, controllers and sensors exchange data packet across the communication network. This delay can degrade the performance of control systems and can even destabilize the system. An extensive study on time delay systems can be found in the research area. Since the network is utilized to transmit packets of the sampled values of the output/state of the system, and several systems might be connected to the same network, delay is inevitable and might cause deterioration of the system performance.

There are several references that deal with the delay involved in NCS and the control loop experiences constant and varying time delays. In the literature, the varying delays are often referred to as jitter. Many traditional control design methods are based on the assumption of time delays, but this is rarely the case in NCS. Therefore new control schemes are needed for NCS with the presence of jitter. Therefore the field of NCS has lately been widely researched.

The computational times of the controllers may also vary depending on the complexity of the control algorithm. Thus computational delay may become a severe problem.

In control loop closed over networked control systems, data (manipulated and controlled variables) are sent and received by network nodes. The main processing activities that occur at each control loop execution, specially, for a closed loop, is schematically shown in Figure 2.4, are:
• The sensor node samples the process output with a constant sampling period (activity that include the analog to digital conversion, codification and packing of the message) which is sent to the controller. The time taken for these activities introduces sampling computational delay $\tau_s$.

• The controlled variables are sent from the sensor to the controller node introducing communication delay $\tau_{sc}$.

• The controller node upon receiving the message, unpacks and decodes the message, and calculates the control signals to be sent to the actuator node by using a control algorithm, and then prepares, codifies and packs a new message, which introduces a control algorithm computational delay $\tau_c$.

• The control signals are sent from the controller to the actuator node, introducing a communication delay $\tau_{ca}$.

• The actuator node, upon receiving the message, obtains the manipulated signals after the digital-to-analog conversion are applied to the process, which introduces a new actuator computational delay $\tau_a$.

The accumulation of all network delays, called sampling-actuation delay is given by Equation (2.1).

$$\tau = \tau_s + \tau_{sc} + \tau_c + \tau_{ca} + \tau_a$$ (2.1)

Note that $\tau$ in general, cannot be considered to be constant. Network induced delays ($\tau_{sc}$ and $\tau_{ca}$) may vary depending on the chosen hardware, network traffic and protocol. Computational induced delays ($\tau_s$, $\tau_c$, $\tau_a$) may vary depending on the scheduling, processing nodes load, etc. However, since this research work is interested on evaluating the effects of communication
induced delays in the performance of the NCS, henceforth as Chow and Tipsuwan (2003) it is assumed that the computational delays as are small constants, or neglected because these delays are usually small compared to $\tau_{\text{sc}}$ and $\tau_{\text{ca}}$. To illustrate, an overall real time NCS is considered in Figure 2.5.

![Figure 2.4 Closed loop processing activities](image)

The remote unit receives the control signal $u_{R}(t)$ sent from the central controller as $u_{C}(t)$, which can be mathematically expressed as Equation (2.2).

$$u_{R}(t) = u_{C}(t - \tau_{\text{ca}})$$  \hspace{1cm} (2.2)

The remote unit also sends the sensors output signal $y_{R}(t)$ of the remote system back to the controller $y_{C}(t)$, and these two signals are related as in Equation (2.3).

$$y_{C}(t) = y_{R}(t - \tau_{\text{sc}})$$  \hspace{1cm} (2.3)
2.4.3 Communication Network

CAN, Profibus, etc. are the several standard industrial networks which are widely used for networked control systems for years. Most of these networks have deterministic delays and bandwidth to perform networked closed-loop control using available control techniques without causing significant performance degradation or instability. However, in today’s competitive market environment the investment on expensive network devices of these protocols is a problematic factor. Due to disturbances in network environments or changes in network user demands, such as the loss of a link, the availability of network resources may change unexpectedly. Therefore, the end-to-end control devices may have to renegotiate with the network resource counterparts for reallocation.

The functions of network variables such as the network throughput, the network management/policy used, the network protocol used, the number and type of signals to be transmitted, the network traffic congestion condition, packet dropouts, and the controller processing time are taken as the current network condition n(t) and let $z^{-1}$ be a time delay operator which defines the signal as in Chow and Tipsuwan (2003)
2.5 MODELING DC MOTOR

A networked control system can be divided into the central controller, the remote unit, and the data network. The remote unit generally consist the plant. The remote unit plant chosen in this thesis is a DC motor. The remote unit receives the control signal from central controller and sends the measured signals to the central controller.

The DC motors are used in various applications such as industries, defense, robotics, etc. DC motors are used extensively because of their simplicity, favorable cost, reliability, ease of application, and have long been a backbone of industrial applications. DC motors have a long tradition of use as adjustable speed machines and a wide range of options have evolved for this purpose. The DC motors are broadly classified into (a) sliding contact motors with commutator and brushes and (b) brushless or contact less motors with SCR/transistor commutator. The sliding contact motors may be classified into permanent magnet motors and electromagnetic field motors. The electromagnetic field armature controlled motor is considered.

An armature controlled DC servomotor is a DC shunt motor designed to satisfy the requirement of a servomotor. If the field current is constant, the speed is directly proportional to armature current. Hence the torque and speed can be controlled by armature voltage. Reversible operation is possible by reversing the armature voltage. In small motors, the armature voltage is controlled by a variable resistance. But in rare motors in order to reduce power loss, armature voltage in controlled by thyristors. Figure 2.6 shows an armature-controlled DC motor.
Figure 2.6 Armature Controlled DC motor

In this system, R - resistance of armature winding (in ohms), L - inductance of armature winding (in henrys), \( i_a \) - armature current (in amperes), \( i_f \) - field current (in amperes), \( u(t) = e_a \) - applied armature voltage (in volts), \( T \) - torque developed by motor (in N-m), \( \theta \) - angular displacement of motor shaft (in radians), \( J \) - equivalent moment of inertia of motor and load referred to motor shaft (in kgm\(^2\)), \( B \) - equivalent viscous friction coefficient of motor and load referred to motor shaft (in N-m/rad/s) and \( \omega \) - rotor angular speed (in radian/sec) = d\( \theta \)/dt

In servo applications, the DC motors are generally used in the linear range of the magnetization curve. Therefore, the air gap \( \Phi \) is proportional to the field current, i.e.

\[
\Phi \propto i_f
\]

\[
\Phi = K_f i_f \text{ where } K_f \text{ is a constant.}
\]

The torque \( T \) developed by the motor is proportional to the product of the air gap flux \( \Phi \) and the armature current \( i_a \) (i.e.)
\[ T = \Phi i_a \]

i.e. \[ T = K_1 j i_a \]

or \[ T = K_1 j i_a \] where \( K_1 \) is a constant.

In the armature controlled DC motor, field current is kept constant, so that the equation for \( T \) can be written as

\[ T = K_i i_a \]

where \( K \) is known as the motor torque constant.

The motor back emf is proportional to speed (i.e.)

\[ e_b \alpha \frac{d\theta}{dt} \]

\[ e_b = K_b \frac{d\theta}{dt} = K_b \omega \]

or

where \( K_b \) is the back emf constant.

The differential equation of the armature circuit is

\[ u(t) = e_a = L \frac{di_a}{dt} + Ri_a + e_b \]

\[ = L \frac{di_a}{dt} + Ri_a + K_b \omega \]  \hspace{1cm} (2.4)

The torque equation is

\[ T = K_i i_a = J \frac{d\omega}{dt} + B \omega \]  \hspace{1cm} (2.5)
By designating the state variables $i_a$ and $\omega$ as $x_1$ and $x_2$ respectively and the output $\omega$ as $y(t)$, the state equations are described as

$$\frac{di_a}{dt} = \frac{R}{L} i_a - \frac{K_b}{L} \omega + \frac{1}{L} u$$  \hspace{1cm} (2.6)

$$\frac{d\omega}{dt} = \frac{K}{J} i_a - \frac{B}{J} \omega$$ \hspace{1cm} (2.7)

Substituting $x_1 = i_a$ and $x_2 = \omega$ in Equations (2.6) and (2.7), the state Equations (2.8) and (2.9) are obtained

$$\dot{x}_1(t) = -\frac{R}{L} x_1 - \frac{K_b}{L} x_2 + \frac{1}{L} u$$  \hspace{1cm} (2.8)

$$\dot{x}_2(t) = \frac{K}{J} x_1 - \frac{B}{J} x_2$$ \hspace{1cm} (2.9)

Output equation

$$y = \omega = x_2$$

Therefore the state model is

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{K_b}{L} \\ \frac{K}{J} & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} u(t)$$  \hspace{1cm} (2.10)

$$y = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$ \hspace{1cm} (2.11)

Comparing state Equations (2.8) and (2.9) and output equation, the state model of linear time invariant systems can be formed in general as

$$\dot{x}(t) = Ax(t) + Bu(t)$$

$$y(t) =Cx(t) + Du(t)$$
From the equations (2.10) and (2.11) the following are written:

\[
A = \begin{bmatrix} -\frac{R}{L} & -\frac{K_b}{L} \\ K/J & -B/J \end{bmatrix}
\]

\[
B = \begin{bmatrix} 1/L \\ 0 \end{bmatrix}
\]

\[
C = \begin{bmatrix} 0 & 1 \end{bmatrix}
\]

and \( D = 0 \)

From Chow and Tipsuwan (2003), the parameters of the motor as given in Table 2.1 are used and the following are obtained.

\[
A = \begin{bmatrix} -0.552 & -0.0865 \\ 6.93 & -1.11 \end{bmatrix}
\]

\[
B = \begin{bmatrix} 0.118 \\ 0 \end{bmatrix}
\]

\[
C = \begin{bmatrix} 0 & 1 \end{bmatrix}
\]

**Table 2.1 DC Motor parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>Moment of Inertia</td>
</tr>
<tr>
<td>L</td>
<td>Inductance</td>
</tr>
<tr>
<td>R</td>
<td>Resistance</td>
</tr>
<tr>
<td>B</td>
<td>Damping Coefficient</td>
</tr>
<tr>
<td>K</td>
<td>Torque Constant</td>
</tr>
<tr>
<td>K_b</td>
<td>Back EMF constant</td>
</tr>
</tbody>
</table>
2.6 SUMMARY

The chapter explains the overview of the networked control systems, their operations as hierarchical and direct methods. DC motor model is constructed and the network challenges are discussed. The detailed survey on networked control systems and networked DC motor control systems are also reviewed in this chapter.