Contemplate Approach of Design and Analysis of Networked Control System

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Abstract
Real time distributed system with smart agents that can communicate and interact with environment through a common communication medium is called a Networked Control System (NCS). Dependency on communication systems increases, the bandwidth of medium became the hindrance to the Networked Control System. This led the researchers to focus on control systems, apart from communication networks. Prominent challenges in integrating control and communication are network induced delay, packet dropouts, scheduling strategies, network load, efficient bandwidth utilization, stability and desired characteristics of the system. This article focuses on the issues involved in the design and implementation of NCS from communication as well as control point of view. The different delays involved in NCS are analysed and proposed methods to overcome delays using compensator are also discussed.

Keywords: Maximum Allowable Delay Bound (MADB), Networked Induced Delay (NID), Networked Control system (NCS), Quality of Performance (QOP), Quality of Service (QOS)

1. Introduction
The state of art in industrial and manufacturing systems is to amalgamate computing, communication and control into various levels of factory/machine information and operation processes. Feedback loops that are coupled with a communication network have become more and more common as the integration of hardware devices became cheaper. Over the past decade, major developments in the field of communication and computer networks have made it possible to include them in feedback systems in order to ensure stability and performance of the system. This led to a new concept in control system analysis and design, called Networked Control Systems (NCS).

The elements of NCS such as sensors, controllers, actuators and communication network provides data transmission between devices to be able to enable resource sharing and task scheduling across different locations. NCS is widely used in manufacturing industries for automation, robots, advanced aircraft and electrified transportation, Unmanned Aerial Vehicle (UAVS), etc., Within NCS, all the real time sensory and feedback messages are transmitted through network and the nodes must finish the controlling task through coordinated manipulation.

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The flexible system design, modularity, ease of implementation, simple wiring, ease of operation and maintenance are the advantages of NCS over the traditional end to end control systems. Figure 1 shows the schematic diagram for an NCS.

NCS is made of Sensors, Controller, Actuators and Communication Network.

**Sensor:** It senses the plant output in the form of analog signal and convert them into a digital signal. It is time-triggered.

**Controller:** It computes the required control signal for the plant and sends it to the actuator through communication network. It is event-triggered.

**Actuator:** It receives the digital signal and converts into an analog signal. This signal will be sent to the plant. It is event-triggered.

**Communication Network:** It connects the sensor, controller and actuator nodes.

The point to point architecture used in conventional control systems does not experience any delay in data exchange whereas, time delays are introduced between sensor, actuator and controller due to common bus architecture. These delays are due to sharing of network as well as the estimation time necessary for signal coding and communication processing. Depending on the network protocols, scheduling algorithms and chosen hardware, delays might be constant, bounded or random. The performance of the plant/system can be degraded by these time varying delays and even affect the stability of the system. Also, there is an opportunity that sensor and control signals may get demised in the communication. These efforts have stimulated a physically powerful study interest in NCS within the control society.

## 2. Communication Strategies in the Design of NCS

NCS is a digital real-time control system, where sensor transmits the signal to the controller via a shared network and controller calculates the control signal and transmits to the plant/actuator through the same shared communication medium. The vital factor restraining desired characteristics and performance is time availability of these resources for sensor, controller and actuator.

The most common, reliable and confined way of linking nodes communicating over an industrial network is by cables. There are numerous technologies for use in industrial applications which are developed and supported by a number of device manufacturers. Wired communication channels and their communication protocols are the most common, reliable and protected way of connecting nodes communicating over an industrial network. In the recent times, wireless communication networks have become very popular and there are numerous technologies for use in industrial applications where the main difference is in the data transfer rates and communication Protocols. Protection from unauthorized access, data encryption and decryption techniques are to be considered while designing NCS, if it is a wireless network. The incorporation of the communication medium in the closed control loop formulates the examination and design of an NCS difficult, as it involves lot of parameters that need to be considered in NCS design.

### 2.1 Network Induced Delay

Since a common network is shared by all the physical components, the diverse delays with uneven lengths occur. Delays induced in the NCS system are (a) sensor to controller Delay $T_{sc}$, (b) Controller to actuator Delay $T_{ca}$, (c) Controller Computation time; $T_c$. With the use of sophisticated processors, computation time can be minimized and can be ignored in the delay analysis. However, communication delays can deteriorate the characteristics of the system and also affect stability of the system.

Figure 2 depicts the schematic of a feedback control loop for a single-input and single-output (SISO) system with network-induced delays.

![Control Loop for Single Input, Single Output System with Network-Induced Delays](image)

Figure 2. Control loop for Single Input, Single Output system with network-induced delays.

Figure 3 shows Networked Induced Delays (NID) between sensor, controller and actuator. NIDs are ran-
dom in nature, as it is a strong function of overhead time, network protocols, scheduling method and transmission errors\(^5\). These delays cannot be eliminated, but can be reduced by optimally using the network resources, bandwidth and scheduling techniques\(^6\).

2.2 Sampling Period

The sampling period has a major impact in NCS design. The samples should be sent within the sampling period to ensure proper performance of the system. The performance of the system will be better if the sampling period is larger but may result in less utilization of network resources\(^6\).

The smaller the sampling period, more is the data transmission resulting in network congestion, still worsening the delay, packet losses and performance of the system\(^\text{2}^\text{,}\text{3}\). Hence, Sampling period is a compromise between Quality of service (QOS) and Quality of Performance (QOP)\(^1\text{0}\text{,}\text{1}\text{1}\). The effect of delays on control systems can be reduced by using time varying sampling algorithms. Sampling period can be time varying for a single loop, whereas sampling period of each loop is different in multiple loop control systems.

2.3. Scheduling

The challenge in network scheduling of NCS is to allocate the network to various nodes based on the scheduling algorithm. A transmission entity can be a sensor or a set of sensors of the plant. Network scheduling in an NCS is about which data is transmitted and when, and with what priority when collision happens. Static scheduling algorithms may perform badly since they do not have mechanisms to examine the function and adjust the priority of scheduling according to new and unpredictable situations\(^1\text{2}\).

Dynamic algorithms can dynamically alter the priorities of control loops, ensuring stability of the system, better utilization of network resources with associated complexities.

3. Control Strategies in the Design of NCS

The stability and delay characteristics are the main aspects to be considered in the controller designs. There are many challenges like Communication delay, Packet Drop out, Bandwidth constraints, etc., in the design of feedback control system due to shared communication network. This led the researchers to focus on the design of different controllers to improve the performance of feedback system.

Different controllers have been designed by researchers to overcome the challenging issues. There are various...
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delay compensation schemes: Smith Predictor, Linear Quadratic Regulator (LQR) control, fuzzy control, Adaptive control, intelligent control and robust control. These control strategies can be modified to compensate time delays to assure the stability of the system. Use of PID controller is discussed in [13,14]. Neural network technique is analysed in the closed loop system [15]. The fuzzy control can be combined with classical control theory to enhance the stability of the system. The inclusion of estimator in the closed loop reduces the number of times a sensor communicate with the controller and also helps to improve stability of the system when there are communication delays or packet drop outs. J. Nilsson et al. [16] considered the stochastic optimal LQG controller and analysed the outcome of networked induced delay with a hypothesis that network induced delay is less than sampling period. Design of Robust controller design is discussed in [17]. Delay estimation techniques and delay compensation algorithms have been anticipated to improve the quality of service and performance [18]. The performance of NCS with different compensation schemes have been analysed for time varying delays. Design of compensator is complex when network induced delay is more than a sampling period as it will increase the network load and message rejection.

4. Challenges in the Design of NCS

The design of NCS is very complex as it involves coordination of both control and communication. The Maximum Allowable Delay Bound (MADB) is explained in [19,20]. It is the maximum allowable time from the moment, when the sensors intellect the data from a system to the moment, when actuators yield the control signals to the plant. The reliability of the system cannot be assured if the delay exceeds Maximum Allowable Delay. Usually a higher sampling rate is preferred in most of the systems to get better performance, but may increase network loads, which will subsequently increase delay periods thereby exceeding MADB, affecting stability of the system [21,22].

In order to balance network loads, it is necessary to choose proper network scheduling algorithm and network protocols. The choice of scheduling algorithm depends on the amount of network traffic to be handled in real time and hence on the sampling rate. The delay in the feedback loop is due to increased network load, higher sampling rate, packet drop outs, message collision, node failures, etc., Hence, Control and Communication are closely associated with each other in NCS.

The traditional controller design requires to be modified to suite the challenges involved in the design of networked control system [23]. Better Network protocols or scheduling method need to be proposed.

5. Conclusion

The problems associated in the design and modelling of Networked control system is discussed. The complexity involved in the design of NCS involves study of controller techniques and communication strategies like scheduling algorithm and network protocols. The techniques which reduce or compensate network induced delay need to be proposed ensuring stability of the system. The different factors that want to be considered in the design are sampling period or rate, communication channel, network induced delay, network protocols, scheduling algorithm, network congestion, packet loss, controller design, compensation schemes etc. The stability of the system cannot be ensured if delays are not considered in the design. Hence, proper scheduling algorithm, sampling rate should be associated with delay compensation schemes to ensure performance of the system.

6. References

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