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Overview of Networked Control Systems

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Abstract. Networked control systems (NCS) have been one of the main research focuses in academia as well as in industrial applications for many decades. NCS has taken the form of a multidisciplinary area. In this chapter, we introduce NCS and the different forms of NCS. The history of NCS, different advantages of having such systems are the starting points of the chapter. Furthermore, the chapter gives an insight to different challenges which come with building efficient, stable and secure NCS. The chapter talks about different fields and research arenas, which are part of NCS and which work together to deal with different NCS issues. A brief literature survey concerning each topic is also included in the chapter. iSpace is the test-bed for NCS and it attends the practical issues and implementation of NCS. At the end, iSpace at ADAC is presnted as a case study for NCS with different experimental results.

Keywords. Networked control systems, time-sensitivity, intelligent space, UGV navigation.

1.1 Introduction

A control system is a device or set of devices to manage, command, direct or regulate the behavior of other devices or systems. In engineering and mathematics, control theory deals with the behavior of dynamical systems. Although control systems of various types date back to antiquity, a more formal analysis of the field began with a dynamics analysis of the centrifugal governor, conducted by the famous physicist Maxwell in 1868 entitled "On Governors." A notable application of dynamic control was in the area of manned flight. The Wright brothers made their first successful test flights on December 17, 1903 and were distinguished by their ability to control their flights for substantial periods (more so than the ability to produce lift from an airfoil, which was known). Control of the airplane was necessary for flight safety. For many years, researchers have given us precise and optimum control strategies emerging from classical control theory, starting from open-loop control to sophisticated control strategies based on genetic algorithms.

The advent of communication networks, however, introduced the concept of remotely controlling a system, which gave birth to networked control systems (NCS). The classical definition of NCS can be as follows: When a traditional feedback control system is closed via a communication channel, which may be shared with other nodes outside the control system, then the control system is called an NCS [15]. An NCS can also be defined as a feedback control system wherein the control loops are closed through a real-time network. The defining feature of an NCS is that information (reference input, plant output, control input, etc.) is exchanged using a network among control system components (sensors, controllers, actuators, etc., see Fig. 1.1).

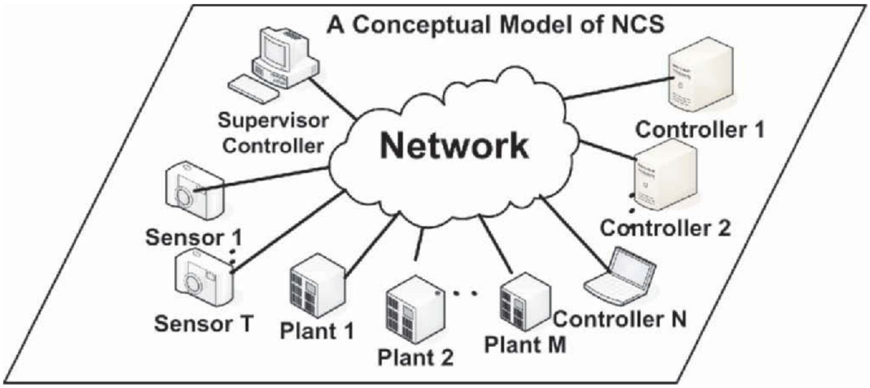

Fig. 1.1. A typical networked control system

1.1.1 Advantages and Applications of Control over Network

For many years now, data networking technologies have been widely applied in industrial and military control applications. These applications include manufacturing plants, automobiles, and aircraft. Connecting the control system components in these applications, such as sensors, controllers, and actuators, via a network can effectively reduce the complexity of systems, with nominal economical investments. Furthermore, network controllers allow data to be shared efficiently. It is easy to fuse the global information to take intelligent decisions over a large physical space. They eliminate unnecessary wiring. It is easy to add more sensors, actuators and controllers with very little cost and without heavy structural changes to the whole system. Most importantly, they connect cyber space to physical space making task execution from a distance easily accessible (a form of tele-presence). These systems are becoming more realizable today and have a lot of potential applications [16, 20], including space explorations, terrestrial exploration, factory automation (Fig. 1.2), remote diagnostics and troubleshooting, hazardous environments, experimental facilities, domestic robots, automobiles, aircraft, manufacturing plant monitoring, nursing homes or hospitals, tele-robotics (Fig. 1.3) and tele-operation, just to name a few.

Fig. 1.2. Factory automation

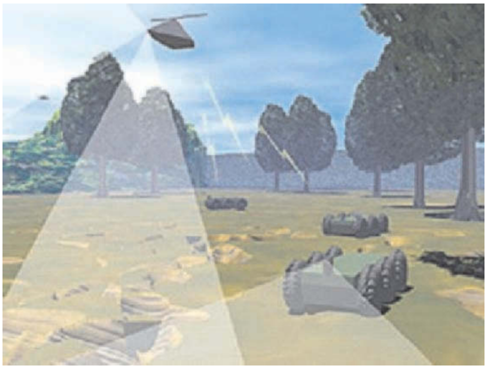

Fig. 1.3. Unmanned ground vehicle navigation (image courtesy of Space and Naval Warfare Systems Center, San Diego)

1.1.2 Brief History of Research Field of NCS

The advent of the Internet gave a huge base for millions of smaller domestic, academic, business, and government networks, which together carry information and services, such as electronic mail, online chat, file transfer, interlinked web pages and other documents of the World Wide Web. In the last few years, there has also been a tremendous increase in the deployment of wireless systems, which has triggered the development and research of distributed NCS. As the concept of NCS started to grow because of its potential in various applications, it also provided many challenges for researchers to achieve reliable and efficient control. Thus the NCS area has been researched for decades and has given rise to many important research topics. A wide branch in the literature focuses on different control strategies and kinematics of the actuators/vehicles suitable for NCS [2], [19], [26], [45]. Another important research area concerning NCS is the study of the network structure required to provide a reliable, secured communication channel with enough bandwidth, and the development of data communication protocols for control systems [2], [23], [35]. Collecting real-time information over a network using distributed sensors and processing the sensor data in an efficient manner are important research areas supplementing NCS. Thus NCS is not only a multidisciplinary area closely affiliated with computer networking, communication, signal processing, robotics, information technology, and control theory, but it also puts all these together beautifully to achieve a single system which can efficiently work over a network. For example, a robot which is in the eastern part of the world can be controlled by a person sitting in the USA (Fig. 1.4) [8].

Some of the well-known research institutes and research labs working in NCS are listed below.

Advanced Diagnosis, Automation and Control (ADAC) Laboratory at North Carolina State University (http://www.adac.ncsu.edu/).

Alleyne Research Group at University of Illinois at Urbana-Champaign (http://mr-roboto.me.uiuc.edu/).

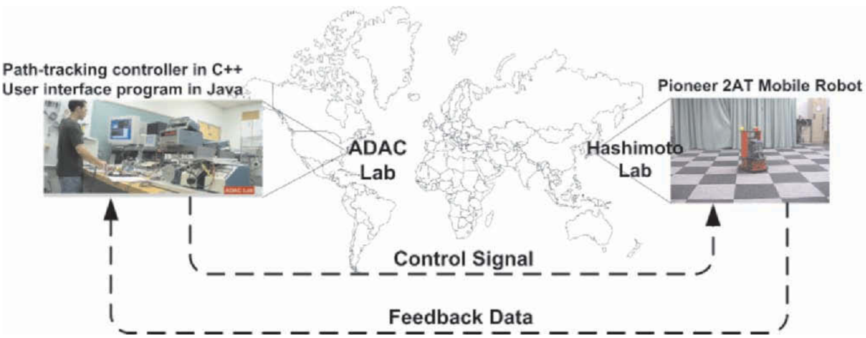

Fig. 1.4. Remote mobile robot path-tracking via IP setup between ADAC lab (USA) and Hashimoto lab (Japan)

Networked Control Systems Laboratory at University of Washington (Seattle) (http://www.ee.washington.edu/research/ncs/index.html).

Center for Networked Communicating Control Systems (CNCS) at University of Maryland at College Park (http://www.isr.umd.edu/CNCS/).

Network Control Systems Laboratory at National Taiwan University (http://cc.ee.ntu.edu.tw/∼ncslab/).

Interdisciplinary Studies of Intelligent Systems at University of Notre Dame (http://www.nd.edu/∼isis/).

1.2 NCS Categories and NCS Components

Generally speaking, the two major types of control systems that utilize communication networks are (1) shared-network control systems and (2) remote control systems. Using shared-network resources to transfer measurements, from sensors to controllers and control signals from controllers to actuators, can greatly reduce the complexity of connections. This method, as shown in Fig. 1.5, is systematic and structured, provides more flexibility in installation, and eases maintenance and troubleshooting. Furthermore, networks enable communication among control loops. This feature is extremely useful when a control loop exchanges information with other control loops to perform more sophisticated controls, such as fault accommodation and control. Similar structures for network-based control have been applied to automobiles and industrial plants.

On the other hand, a remote control system can be thought of as a system controlled by a controller located far away from it. This is sometimes referred to as tele-operation control. Remote data acquisition systems and remote monitoring systems can also be included in this class of systems. The place where a central controller is installed is typically called a "local site," while the place where the plant is located is called a "remote site."

There are two general approaches to design an NCS. The first approach is to have several subsystems form a hierarchical structure, in which each of the subsystems contains a sensor, an actuator, and a controller by itself,

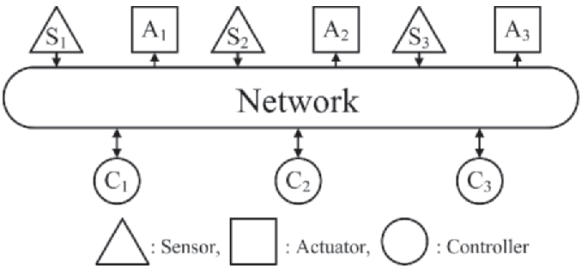

Fig. 1.5. Shared-network connections

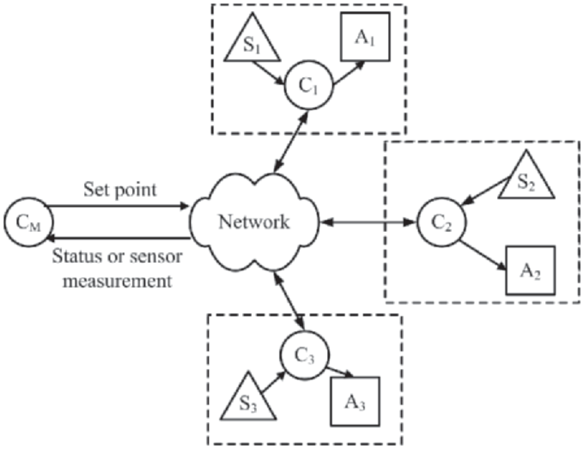

Fig. 1.6. Data transfers of hierarchical structure

as depicted in Fig. 1.6. These system components are attached to the same control plant. In this case, a subsystem controller receives a set point from the central controller CM. The subsystem then tries to satisfy this set point by itself. The sensor data or status signal is transmitted back via a network to the central controller.

The second approach of networked control is the direct structure, as shown in Fig. 1.7. This structure has a sensor and an actuator of a control loop connected directly to a network. In this case, a sensor and an actuator are attached to a plant, while a controller is separated from the plant by a network connection.

Both the hierarchical and direct structures have their own pros and cons. Many networked control systems are a hybrid of the two structures. For example, the remote teaching lab is an example that uses both structures [7], [10].

Networked control applications can be divided into two categories: (1) time-critical/time-sensitive applications and (2) time-delay-insensitive applications. In time-delay-sensitive applications, time is critical, i.e., if the delay-time exceeds the specified tolerable time limit, the plant or the device can either be damaged or produce inferior performance. An example of time-

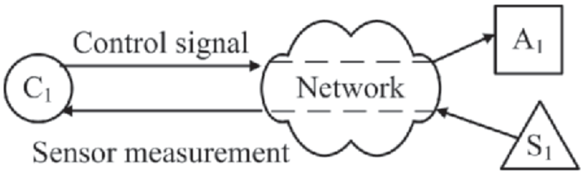

Fig. 1.7. Data transfers of direct structure

delay-sensitive applications is tele-operation via networks for fire-fighting operations, undersea operations, and automated highway driving. On the other hand, time-delay insensitive applications are tasks or programs that run in real time but whose deadlines are not critical. Examples of these applications are e-mail, ftp, DNS, and http. We will briefly mention many advantages of networked control systems, tele-operation being the most evident and tangible one. Let us categorize the NCS according to the amount of human interference in the loop.

(1) Tele-operated systems with human operator–In this case, a human operator from one location controls the actuators (robots, arms, unmanned vehicles) at different locations. The feedback to the operator is mainly visual (video or real-time image). The precision and accuracy of the system operation also depends upon operator skill including system precision, feedback delay and accuracy, signal distortion. This can also be called the *human supervisory control* [33]. Therefore for such tele-operated systems, many times, the human operators are required to be trained to operate the system. There are various applications of such systems like distributed virtual laboratories, remote surgery systems [14], field robotics, etc. Such systems therefore suffer from issues like human perception accuracy, force feedback to the operator, network delay, control prediction, ergonomics, security, system portability, etc. [4], [34]. There are also many tools developed for accurate operator feedback such as virtual reality (VR), interactive televisions, 3-D visualization environment, etc. [4]. One of the VR environments developed by Alfred E. Mann Institute at USC is used to simulate the movement of prosthetic limbs and human limbs. Its main use is to prototype the control of the prosthetic systems and fit the control to patient needs. It also allows the patients to train in VR to operate their prosthetic limbs (Fig. 1.8).
(2) Tele-operation without human intervention–In such systems the intelligence is built inside the controller modules. The sensor data and actuator feedback data is directly fed to the controller over the network. This can also be called the *autonomous networked control system*. The supervisory controller is not a human in this case. A human can act as an external user which can choose tasks or specify some manual control commands. Such systems are therefore not dependent on human perception and do not require operators to be skilled or trained. However developing intelligent and efficient data processing and controlling algorithms for supervisory control is very important. Supervisory controllers can use techniques such as machine learning, neural networks and artificial intelligence algorithms to take intelligent operation decisions. In this case, sensor data fusion and actuator bandwidth optimization and scheduling are equally important issues to be considered.
(3) Hybrid control: Main controller and actuator have distributed intelligence to increase the efficiency of network operations.

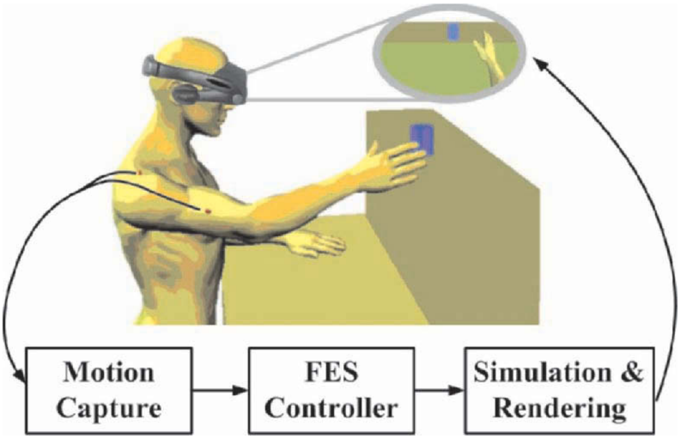

Fig. 1.8. Virtual reality (image courtesy Alfred E. Mann Institute, USC)

Here in this chapter we will focus mainly upon time-sensitive supervisory networked control systems.

1.2.1 NCS Components

Whatever the arrangement or modalities used for connecting and configuring the hardware and the software assets in order to actualize a networked control system that has certain capabilities, the components used have to enable four functions which form the basis of the function an NCS is required to project. These basis functions are information acquisition (sensors), command (controllers), and communication and control (actuators).

1.2.2 Information Acquisition in a Network

As the name suggests information acquisition requires us to study sensors, data processing, and signal processing. There is a growing excitement about the potential application of large-scale sensor networks in diverse applications such as precision agriculture, geophysical and environment monitoring, remote health care, and security [9]. Rapid progress in sensing hardware, communications and low-power computing has resulted in a profusion of commercially available sensor nodes. NCS suggests collecting the relevant data using distributed sensors in the network to study the system under control. Sensor data can be in any form starting from small numbers representing temperature, pressure, weight, etc. or in chunk form such as images, arrays, videos streams, etc. This raises important questions like:

(a) Bandwidth requirements for the data transfer in the network.
(b) Data collection strategies in the case of a number of sensors.

(c) Cheap, reliable and energy efficient sensors which can easily be added to the NCS.

Sensor fusion and sensor networks [11], [40] are very wide research fields which help improve information acquisition in a network. Developing middleware and operating systems for sensor nodes to send data efficiently in the network [29], [30], information assurance [28], energy efficient sensor nodes [44] and sensitivity of the data are the key research foci related to information acquisition in a network. Sensor networks hold the promise of facilitating large-scale, real-time data processing in complex environments.

Image data is used for applications like surveillance [9], robot navigation [27], target tracking [32] and tele-operation, etc. With the advancement in the field of computer vision and image processing, there are many sophisticated algorithms available to process images for pattern recognition and feature extraction. Many systems and algorithms have been developed using visual and other local sensing capabilities to control ground and aerial vehicles [12], [31].

1.2.3 Control of Actuators over a Network

One of the biggest advantages of a system controlled over a network is scalability. As we talk about adding many sensors connected through the network at different locations, we can also have one or more actuators connected to one or more controllers through the network. For many years now, researchers have given us precise and optimum control strategies emerging from classical control theory, starting from PID control, optimal control, adaptive control, robust control, intelligent control and many other advanced forms of these control algorithms. Applying all these control strategies over a network however becomes a challenging task. We will study different issues to be considered for successful and efficient operation of an NCS in the next section.

1.2.4 Communication

The communication channel being the backbone of the NCS, reliability, security, ease of use, and availability are the main focus when choosing the communication or data transfer type. In today's world, plenty of communication modes are available from telephone lines, cell phone networks, satellite networks and, most widely used, Internet. Sure enough, the choice of network depends upon the application to be served. Internet is the most suitable and inexpensive choice for many applications where the plant and the controller are far from each other (as shown in Fig. 1.4, where the controller is in USA and the robot to be controlled is in Japan [7]). The controller area network (CAN) is a serial, asynchronous, multi-master communication protocol for connecting electronic control modules in automotive and industrial applications. CAN was designed for applications needing high-level data integrity and data rates of up to 1 Mbps. Many manufacturing plants have a complete line of products enabling industrial designers to incorporate CAN into their applications.

For years, wireless LANs having been supporting enterprise applications, such as warehouse management and mobile users in offices. With lower prices and stable standards, homeowners are now installing wireless LANs at a rapid pace. LANs for the support of personal computers and workstations have become nearly universal in organizations of all sizes. Even those sites that still depend heavily on the mainframe have transferred much of the processing load to networks of personal computers. Perhaps the prime example of the way in which personal computers are being used is to implement client/server applications. Back-end networks are used to interconnect large systems such as mainframes, supercomputers, and mass storage devices. The key requirement here is for bulk data transfer among a limited number of devices in a small area. High reliability is generally also a requirement.

GPS systems can be used to localize vehicles all over the planet. Military applications, surgical and other emergency medical applications, however, can use dedicated optical networks to ensure fast speed and reliable data communication.

1.3 NCS Challenges and Solutions

After having an overview of different categories, components and applications of NCS, we now describe the different challenges and issues to be considered for a reliable NCS.

We can broadly categorize NCS applications into two categories as (1) time-sensitive applications or time-critical control such as military, space and navigation operations; (2) time-insensitive or non-real-time control such as data storage, sensor data collection, e-mail, etc. However, network reliability is an important factor for both types of systems. The network can introduce unreliable and time-dependent levels of service in terms of, for example, delays, jitter, or losses. Quality-of-service (QoS) can ameliorate the real-time network behavior, but the network behavior is still subject to interference (especially in wireless media), to routing transients, and to aggressive flows. In turn, network vagaries can jeopardize the stability, safety, and performance of the units in a physical environment [21], [36]. A challenging problem in the control of network-based systems is the network delay effects. The time to read a sensor measurement and to send a control signal to an actuator through the network depends on network characteristics such as topology and routing schemes. Therefore, the overall performance of an NCS can be affected significantly by network delays. The severity of the delay problem is aggravated when data loss occurs during a transmission. Moreover, the delays do not only degrade the performance of a network-based control system, but they also can destabilize the system.

(1) Stability in Control and Delay Compensation

For many years now, researchers have given us precise and optimum control strategies emerging from classical control theory, starting from PID control, optimal control, adaptive control, robust control, intelligent control and many other advanced forms of control algorithms. But these control strategies need to be modified according to the application requirements as well as for them to reliably work over a network to compensate for delays and unpredictability. Fig. 1.9 displays the typical NCS model with the time delay taken into consideration. Fig. 1.10 shows the adverse effect of the network delay on a remotely controlled system. It displays the scenario where a mobile agent was asked to track a path with varying curvatures, first with local controller and later with remote controller. As we can observe, without any modifications to the controller, the mobile agent is not able to track the path, especially at the high curvature because of the network delay [7]. Instability of the system due to the network delay is therefore a very important factor to be considered in NCS. Different mathematical, heuristic and statistical-based approaches are taken for delay compensation in NCS. A gain scheduler middleware (GSM) has been developed by Tipsuwan and Chow to alleviate the network time delay effect on network-based control systems. GSM methodology estimates the network traffic and controls the gain of the whole system using a feedback processor as shown in Fig. 1.11. Yu and Yang [46] suggested a predictive control model of NCS to overcome the adverse influences of stochastic time delay, which could improve the performance through model matching and multi-step predictive output compensation. Wang and Wang [43] suggested a delay compensation controller solution with an iterative procedure of a linear matrix inequality (LMI) minimization problem, which is derived from the cone complementarity linearization algorithm.

(2) Bandwidth Allocation and Scheduling

As we talk about having multi-sensor and controlling multi-actuator systems in a network, important consideration should be given to the available bandwidth in the network. With the finite amount of bandwidth available, we want

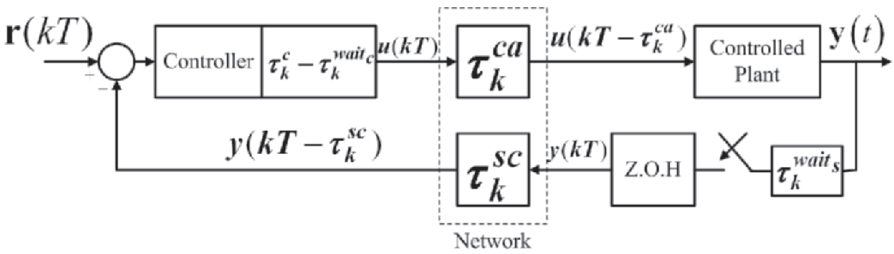

Fig. 1.9. NCS plant structure showing network delays

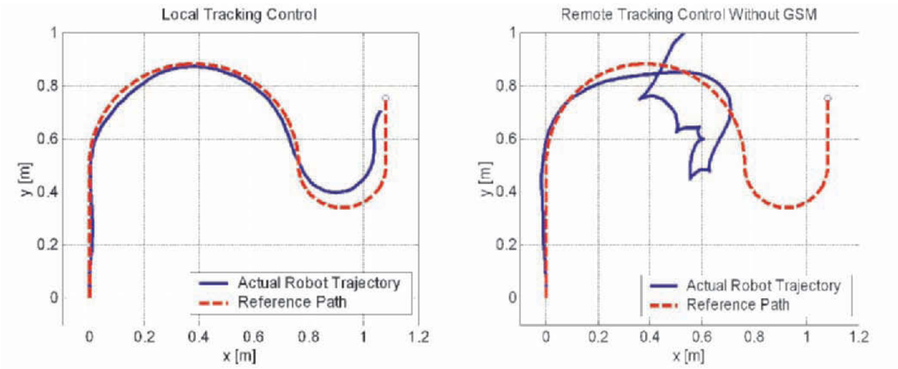

Fig. 1.10. Mobile agent trajectory (1) local control (2) remote control without delay compensation

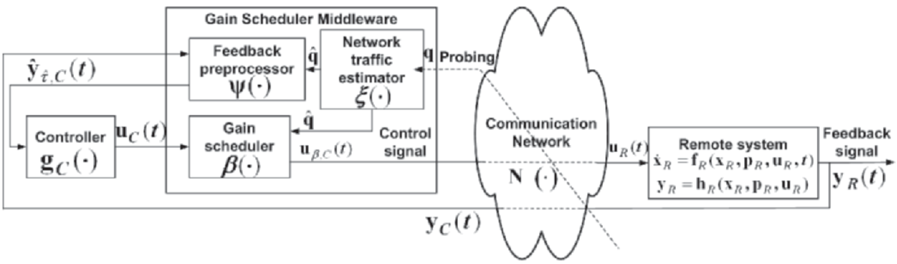

Fig. 1.11. GSM module for network delay compensation

to utilize it optimally and efficiently. This further raises the need for priority decisions and scheduling issues for controlling a series of actuators for a series of tasks [41]. Different scheduling methods and bandwidth allocation strategies have been developed for NCS over the past decade [1], [39]. There are also many tools like Petri-net modeling, integer, nonlinear, dynamic programming, AI tools, genetic algorithms developed for scheduling of networked control systems. Kim *et al.* [18] formulated a method to obtain a maximum allowable delay bound for scheduling networked control systems in terms of linear matrix inequalities. Walsh *et al.* [41] introduced a control network protocol, try-one-discard (TOD), for MIMO NCS. Li and Chow proposed sampling rate scheduling to solve the problem of signal fidelity and conserve the available data transmission [24], [25].

(3) Network Security

All this discussion of sending important sensor and actuator control commands in the network brings us to an important point of security over the network.

Any network medium especially wireless medium is susceptible to easy intercepting; it is extremely critical to protect transmitted data from unauthorized access and modifications in wireless systems. Malicious users can intercept and eavesdrop the data in transit via shared and broadcast medium. Network security includes essential elements in Internet security devices that provide traffic filtering, integrity, confidentiality, and authentication. Therefore data sharing, data classification and data/network security is of utmost concern in distributed networked control systems considering the time and data sensitive applications. In wireless systems, several security protocols such as wired equivalent privacy (WEP), 802.1x port access control with extensible authentication protocol (EAP) support are proposed to address security issues [5], [17]. Moreover, due to strong security provided by IP security protocol (IPsec) in wired networks, it is considered as a good option for wireless systems as well. However, information security and data sensitivity have not been sufficiently addressed to be applied in a real-time NCS. Very few researchers have addressed the trade-off between security addition and real-time operation of NCS. Gupta *et al.* [13] characterize the wireless NCS application on the basis of security effect on NCS performance to show the trade-off between security addition and real-time operation of NCS.

1.3.1 Integration of Components and Distribution of Intelligence

After discussing individual modules involved in NCS and possible issues related to control system, network structure and information acquisition, we come to a point of integrating the components to achieve the final goal. Fusing the global information to make intelligent decisions or to perform a particular task requires integration of different modules like data acquisition, data processing, information extraction, and actuator control. All these different modules perform tasks independently yet together making it one system. Therefore, a few of the issues faced by a network-based navigation system include data sharing, data transfer and interfacing between different modules. Thus it is evident that to improve the efficiency of an integrated networked control system, we not only have to improve each integrated module but also provide an efficient data interface between different modules.

There is a wealth of techniques available for actualizing each one of the basic function modules. A well-designed software architectural framework and middleware are critical for the widespread deployment and proliferation of networked control systems. There are a few system architectures or middleware developed to put such heterogeneous systems together. Component architecture allows individual components to be developed separately and integrated easily later, which is very important for the development of large systems. Further, such architecture promotes software reuse, since a well-designed component such as a control algorithm, tested for one system, can easily be transplanted into another similar system. At the same time suitability of the environment representation for use with the communication and command modules should also be taken into consideration, which is the key point in any practical application of NCS. Baliga and Kumar [3] developed a list of key requirements for such middleware and presented Etherware, a message oriented component middleware for networked control. Tisdale *et al.* [38] from University of California Berkeley also developed a software architecture for autonomous vision-based navigation, obstacle avoidance and convoy tracking. This software architecture has been developed to allow collaborative control concepts to be examined. These architectures represent the system at an abstract level and focus on modularization of the system to achieve flexibility and scalability in design. However, while studying all these modules separately, it is highly unlikely to find a realistic command module that jointly takes into consideration the realization of an admissible control signal when converting a task and constraints on behavior into a group of reference signals. Designing the NCS at the system level by choosing the most suitable and appropriate modules for each component of the NCS is a challenging task. To elaborate more on this point let us look at an example of NCS.

1.4 A Case Study for NCS–iSpace

Intelligent space (iSpace) is a relatively new concept to effectively use various engineering disciplines such as automation and control, hardware and software design, image processing, distributed sensors, actuators, robots, computing processors and information technology over communication networks over a space of interest to make intelligent operation decisions. It can also be considered as a large-scale mechatronic system over networks. This space can be as small as a room or a corridor or can be as big as an office, city or even a planet. ADAC lab at NCSU in Raleigh has developed a multi-sensor network-controlled integrated navigation system for multi-robots demonstrating the concept of iSpace [20]. The modularized structure of iSpace at ADAC is as shown in Fig. 1.12. The information acquisition about the space is through network cameras. The task for the robots is to reach the destination point chosen by the user through the GUI (accessible through internet). All the intelligence to generate navigation commands for the robots resides in the network controller (path generation avoiding the obstacles in the space and path tracking to reach the destination as soon as possible without hitting any of the obstacle in the space).

The system, being an NCS, observes network delay for image acquisition and command transfer from controller to the robot on wireless channels. The image processing, feature extraction and real-time path tracking algorithms are also computationally intensive. The application led to the following choice of different modules to be implemented in the network controller.

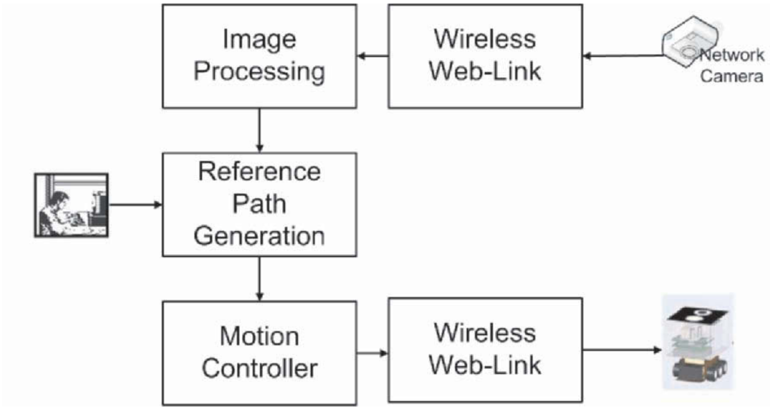

Fig. 1.12. Modularized structure of iSpace at ADAC

(1) HPF for Motion Planning

The use of potential field in motion planning was introduced by Khatib in 1985, where the obstacles were represented by the repelling force and the point of destination was represented by the attractive force. Harmonic potential fields (HPF) were introduced by Connolly to avoid the local minima in navigation. Therefore, tracking the negative gradient from the source in the harmonic potential field map will lead the robot towards the destination as shown in Fig. 1.13 created synthetically to represent obstacle boundaries by white edges and the navigation path for the robot as grey. The HPF equations are given by

$$\begin{aligned}
&\nabla^2\phi(x,y) \equiv 0,\ (x,y) \in \Omega \\
&\text{subject to} \\
&\phi(x,y) = 1,\ (x,y) \in \Gamma \\
&\text{and } \phi(x,y) = -1,\ (x,y) = (x_T, y_T) \\
&\text{and } \phi(x,y) = 0,\ (x,y) \notin \Gamma \text{ and } (x,y) \neq (x_T, y_T)
\end{aligned} \tag{1.1}$$

where ∇^2 is the Laplace operator, Ω is the workspace of the UGV ($\Omega \subset \Re^2$), Γ is the boundary of the obstacles (output of the edge detection stage), and (x_Γ, y_Γ) is the target point. The obstacle free path to the target is generated by traversing the negative gradient of (ϕ), i.e., ($\nabla\phi$).

HPF is a suitable algorithm for path planning on the network controller once the image of the actual space is acquired from the network camera as HPF is computationally fast ($O(n)$ algorithm) and it drives the mobile robot away from the boundaries of the obstacles because of the Dirichlet's settings. Fig. 1.13 shows the path planner created using HPF. All the arrows show the negative gradient direction confirming that UGV is directed away from obstacle boundaries and driven towards the goal point.

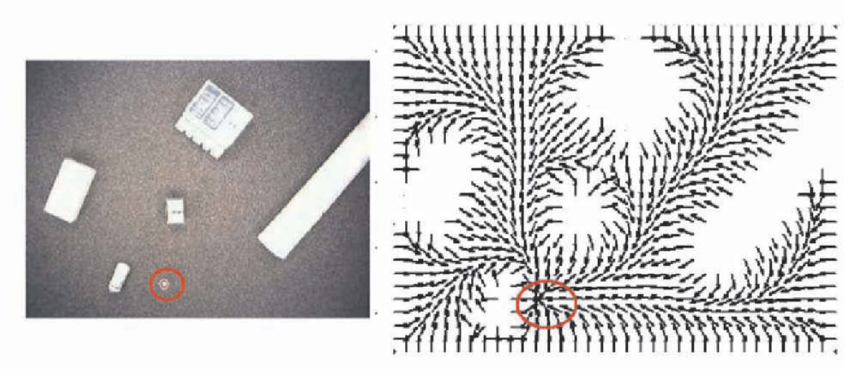

Fig. 1.13. Path planner using the HPF algorithm (goal point shown by the dot in the circle)

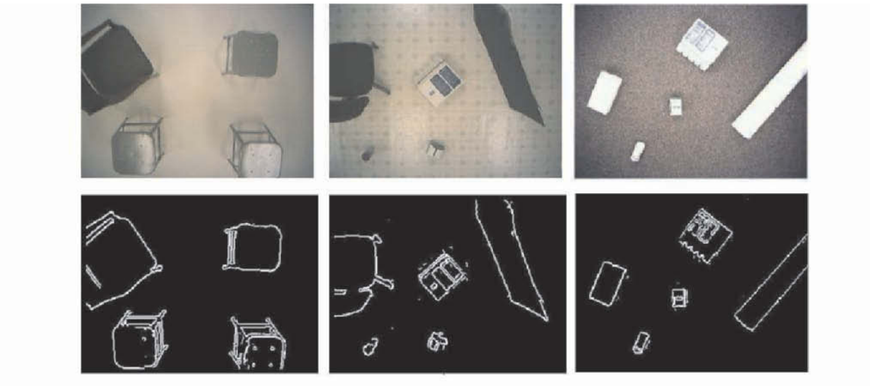

Fig. 1.14. Edge detection results

(2) Edge Detection for Boundary Detection

Converting the actual iSpace image into the raised boundaries of the obstacles is the task of information acquisition as well as data/image processing. Edge detection was used for obstacle boundary recognition. Edge detection is a classic early vision tool to extract discontinuities from the image as features. Thus all the discontinuities, which are more or less obstacle boundaries, will be represented by binary edges in the edge detected image of the UGV workspace. Results are shown in Fig. 1.14. This network-based robot navigation is developed as the research platform for NCS and it is designed for indoor environments. Therefore assuming that the system has enough control over the ambient or artificial light inside the room, cameras are calibrated and fixed, edge detection was a suitable vision feature extractor module to fit in the whole integrated navigation system. The edge maps can be mathematically described by:

$$E(x_i, y_j) = \begin{cases} 1, & \text{if } (x_i, y_j) \in \Gamma \\ 0, & \text{if } (x_i, y_j) \notin \Gamma \quad \text{for all } (i, j) \end{cases} \tag{1.2}$$

where $E(x, y)$ is the image representing the edge map and Γ is the set of boundary points for all obstacles in workspace.

Comparing (1.1) and (1.2), we achieved perfect data interfacing between information processing (edge detection) and motion planning (HPF) module as the output of the edge detection module is directly fed to the HPF planner without any preprocessing.

(3) Path Tracking Using Quadratic Curve Fitting Controller

A quadratic curve fitting path tracking controller is implemented as the motion controller for the UGV to traverse the path from source to the destination point after path planning using HPF is done. The basic principle of this control algorithm, as explained in [45] by Yoshizawa *et al.*, is that a reference point is moved along a desired path so that the length between the reference point and the UGV is kept at some distance (d_0). Control (velocity) commands–speed (v, in cm/s) and turn rate (ω, in rad/s)–are generated for the UGV to reach that reference position from the current position. This algorithm runs in a feedback loop until the UGV reaches its destination point tracking the reference path generated (Fig. 1.15).

The reference point needed for the path tracking algorithm to reach the destination is chosen by looking at the next negative gradient point of the HPF map. As we know, negative gradient following will lead the mobile robot towards the destination avoiding the obstacles according to the property of the HPF map.

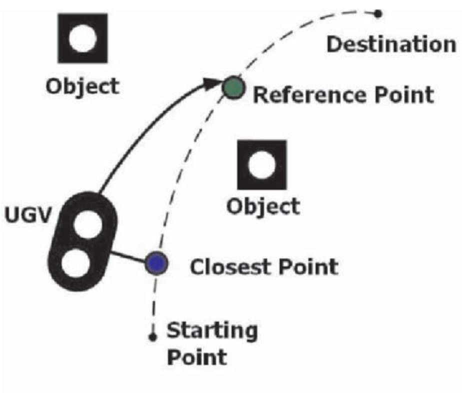

Fig. 1.15. Path tracking control using quadratic curve

(4) Network Delay

As we have been talking about network delay in the NCS, Fig. 1.16 shows the typical network delay graph observed in iSpace operation.

For network delay compensation, we used the gain scheduler middleware technique introduced by Chow and Tipsuwan [36], [37]. GSM methodology uses middleware to modify the output of an existing controller based on a gain scheduling algorithm with respect to the current network traffic conditions. The overall GSM operations for networked control and tele-operation can be summarized as follows [36], [37]. The structure is as shown in Fig. 1.11.

(i) The feedback preprocessor waits for the feedback data from the remote system. Once the feedback data arrives, the preprocessor processes it using the current values of network variables and passes the preprocessed data to the controller.

(ii) The controller computes the control signals and sends them to the gain scheduler.

(iii) The gain scheduler modifies the controller output based on the current values of network variables and sends the updated control signals to the remote system.

Thus, GSM takes care of network delay compensation satisfactorily.

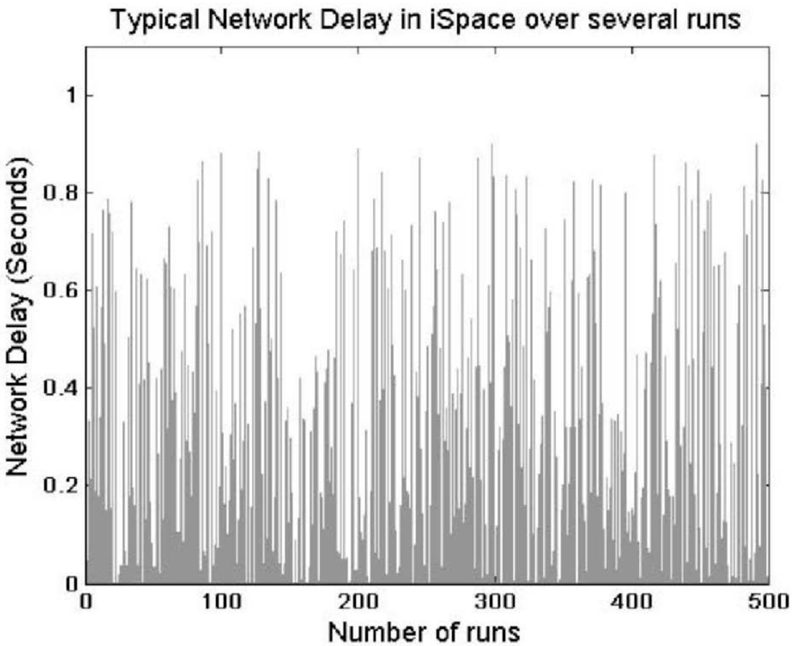

Fig. 1.16. Actual network delay

Fig. 1.17. Navigation results of the networked control navigation system for different environmental patterns. White line is the ideal path and dark line is the actual path traversed by the robot.

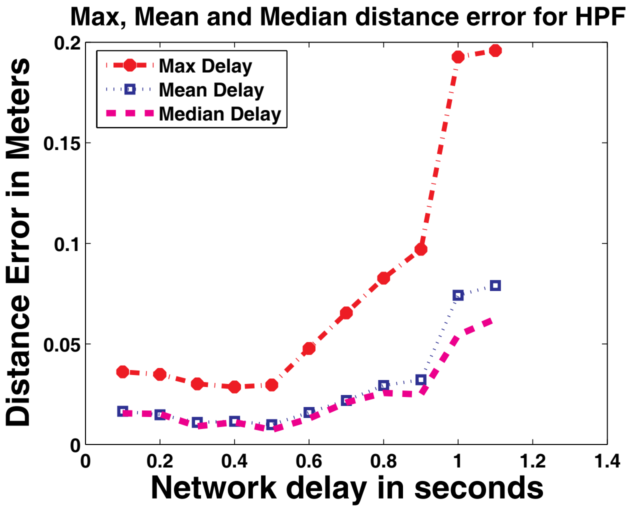

Fig. 1.18. Mean median and max distance error as a function of network delay for iSpace

The choice of individual modules to build the NCS required for indoor robot navigation was done carefully by looking at the data compatibility, environment details, and application requirements. Fig. 1.17 shows some of the experimental results using the NCS structure with edge detection and HPF for UGV navigation in ADAC lab. Fig. 1.18 shows the distance error graph as a function of average network delay for the same experiments. The distance error is the error between the robot's actual navigation path and the ideal path it should have taken with no delays.

Thus, we observe that iSpace, being one form of NCS, the choice of different components, integration of components, and network delay alleviation are important aspects of the system building. These parameters and properties decide the efficiency and operability of the NCS.

1.5 Conclusions

When a traditional feedback control system is closed via a communication channel, which may be shared with other nodes outside the control system, the control system is called a networked control system (NCS). Some of the many advantages of NCS is remote operability, scalability, global fusion of data, globally optimal solutions, etc. NCS can be broadly categorized, depending upon the multi-actuator and multi-sensor structure, as a shared network system and remote control system. It can also be categorized as a time-sensitive/real-time control system and a non-real-time/time-insensitive control system. Human intervention in the feedback loop of the NCS makes it a human supervisory controller having applications like remote operation, remote surgery, etc. On the other hand, autonomous NCS takes the human operator out of the feedback loop and only task- or system configuration-related inputs from human users are accepted, putting all the feedback data directly into the network controller.

NCS is a multidisciplinary research field affiliated with sensor fusion, data processing, control theory, computer networking, communication, security, etc. This leads to research into all fields separately and also poses the challenge of integrating all the modules efficiently. Systems software architectures are developed to design the system on the abstract level, modularize the system such that it becomes scalable and flexible.

There are issues to be considered for QoS of NCS. Network delay, stability, bandwidth allocation, scheduling, modularizing, integration of the modules are some of the key issues considered by the research community to develop an efficient, fast and reliable NCS.

However, NCS has a lot of potential applications like space explorations, terrestrial exploration, factory automation, remote diagnostic/troubleshooting, hazardous environments, experimental facilities, domestic robots navigation, automobiles, etc.

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