Networked Control System: Overview and Research Trends

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Abstract—Networked control systems (NCSs) have been one of the main research focuses in academia as well as in industry for many decades and have become a multidisciplinary area. With these growing research trends, it is important to consolidate the latest knowledge and information to keep up with the research needs. In this paper, the NCS and its different forms are introduced and discussed. The beginning of this paper discusses the history and evolution of NCSs. The next part of this paper focuses on different fields and research arenas such as networking technology, network delay, network resource allocation, scheduling, network security in real-time NCSs, integration of components on a network, fault tolerance, etc. A brief literature survey and possible future direction concerning each topic is included.

Index Terms—Networked control system (NCS), overview, research trends, survey.

I. INTRODUCTION

WHEN A traditional feedback control system is closed via a communication channel (such as a network), which may be shared with other nodes outside the control system, then the control system is classified as a networked control system (NCS). All definitions found in literature for an NCS have one key feature in common. This defining feature is that information (reference input, plant output, control input, etc.) is exchanged among control system components (sensor, controller, actuator, etc.) using a *shared network* (Fig. 1).

The root of control systems can be traced back to 1868 when dynamics analysis of the centrifugal governor was conducted by the famous physicist J. C. Maxwell [1]. The most significant achievement in conventional control systems occurred when the Wright brothers made their first successful test flight in 1903 [2]. The next significant achievement was the fly-by-wire flight control system that was designed to eliminate the complexity, fragility, and weight of the mechanical circuit of hydromechanical flight control systems using an electrical circuit. The simplest and earliest configuration of analog fly-by-wire flight control systems was first fitted to the Avro Vulcan in the 1950s. This can be called as the first form of analog NCSs. Digital computers became powerful tools in control system design, and microprocessors added a new dimension to the
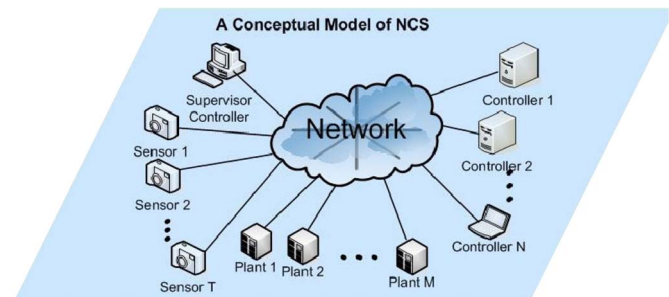
Fig. 1. Typical structure of an NCS.

capability of control systems. A modified National Aeronautics and Space Administration F-8C Crusader was the first digital fly-by-wire aircraft in 1972. The next step in evolution was the distributed control system (DCS) that was introduced in 1975. Both Honeywell and Japanese electrical engineering firm Yokogawa introduced their own independently produced DCSs at around the same time, with the TDC 2000 and CENTUM systems, respectively. As the expanding needs of industrial applications pushed the limit of point-to-point control, it became obvious that the NCS was the solution to achieve remote control operations. Research in teleoperation was initiated with the concern for safety and convenience in hazardous environments, such as space projects and nuclear reactor power plants, and was made feasible only after further development of the NCS.

Later, with the advent of networking technologies, easy and cheap access to the Internet (previously known as ARPANET) proved to be a boon. Friedman emphasizes the effects of the Internet in human activities in his book "*The World is Flat*." Further development and research in NCSs were boosted by the tremendous increase in the deployments of wireless systems in the last few years. Today, NCSs are moving into distributed NCSs [67], which are multidisciplinary efforts whose aim is to produce a network structure and components that are capable of integrating distributed sensors, distributed actuators, and distributed control algorithms over a communication network in a manner that is suitable for real-time applications [10].

This paper is organized as follows (Fig. 2). Section II talks about various NCS classifications in brief. Section III presents the research trends in NCSs for the last five years. This section also includes network delay effects, resource allocation and scheduling, network security, fault-tolerant NCSs, and, finally, successful integration in NCSs. Each research field briefly presents a few examples of NCS to explain the diversity of NCS applications and research platforms. Section IV presents the conclusion and possible future research directions in NCSs.
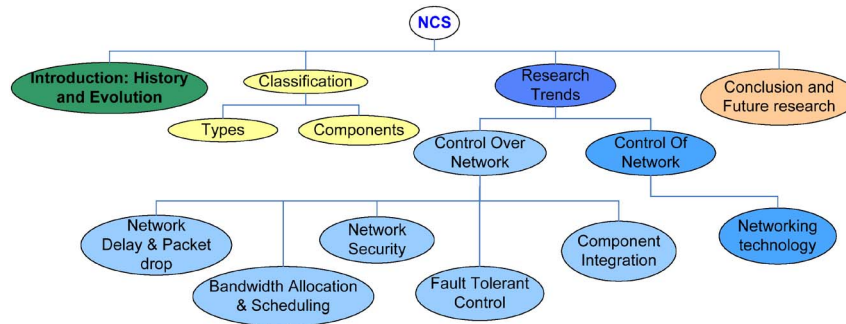
Fig. 2. Tree diagram explaining the structure of this paper.

II. NCS BASICS

The basis capabilities of any NCS are information acquisition (sensors/users), command (controllers/users), communication, and network and control (actuators). In broader terms, NCS research is categorized into the following two parts (Fig. 2).

1) *Control of network.* Study and research on communications and networks to make them suitable for real-time NCSs, e.g., routing control, congestion reduction, efficient data communication, networking protocol, etc.

2) *Control over network.* This deals more with control strategies and control system design over the network to minimize the effect of adverse network parameters on NCS performance such as network delay.

This paper mainly focuses on "control over network" because of the space constraints; however, details about research and evolution of networking technologies for NCSs are in the later section.

Under control over network, there are two major types of control systems that utilize communication networks. They are the following: 1) shared-network control systems and 2) remote control systems. Details, advantages, and suitability of each connection type are explained in [10] with diagrams. Each of the NCS structures has many challenges to maintain the quality of service (QoS) and the quality of control (QoC). In the networks, QoS is the idea that transmission rates, error rates, and other characteristics can be measured, improved, and, to some extent, guaranteed in advance [50]. The QoS can be degraded due to congestion and interference. Thus, the next section moves onto some of these main research topics related to NCS such that QoC and QoS can be maintained.

III. NCS RESEARCH TOPICS AND TRENDS

A. Networking Technologies—Evolution and Research

A communication network is the backbone of the NCS. Reliability, security, ease of use, and availability are the main issues while choosing the communication type.

The ARPANET developed by the Advanced Research Projects Agency of the U.S. Department of Defense in 1969 was the world's first operational packet switching network and the predecessor of the Internet. Later came fieldbus (around 1988)—which is an industrial network system for real-time distributed control. Fieldbus is a generic term which describes a modern industrial digital communication network intended to replace the existing 4–20-mA analog signal standard. This network is a digital bidirectional multidrop serial bus used to link isolated field devices particularly in the automated manufacturing environment. A process field bus is a standard for fieldbus communication in automation technology and was first promoted in 1989 by the German Federal Ministry of Education and Research (BMBF) [57]. Controller–area network (CAN) is one of the other fieldbus standards—which is a serial asynchronous multimaster communication protocol designed for applications needing high-level data integrity and data rates of up to 1 Mb/s. CAN was introduced in 1980s by Robert Bosch GmbH for connecting electronic control units (ECUs) for automotive applications (vehicle bus) [3], following the fly-by-wire technology in flight control. CAN-based DCSs have two main restrictions. They are the size of the distributed area and the need for communication with the following: 1) with other local area networks and 2) with remote CAN segments. Thus, there is a wide variety of competing fieldbus standards, and therefore, many times interoperability becomes an issue. Some of the proposed solutions for this are an extensible device description based on XML [22] and an integrated fieldbus network architecture [21]. Another communication network used in NCSs—Ethernet—has evolved into the most widely implemented physical and link layer protocol today, mainly because of the low cost of the network components and their backward compatibility with the existing Ethernet infrastructure. Now, we have fast Ethernet (10–100 Mb/s) and gigabit Ethernet (1000 Mb/s) [19]. Recently, switched Ethernet became a very promising alternative for real-time industrial applications due to the elimination of uncertainties in the traditional Ethernet [58].

The motivation behind wireless NCS (WNCS) is due to fully mobile operations, flexible installations, and rapid deployments for many compelling applications like automated highway systems, factories, etc. Rapid progress in sensing hardware, communications, and low-power computing has resulted in a profusion of commercially available wireless sensor nodes [20]. Wireless sensor node research in itself is a vast and big research topic; therefore, we do not go into any details in here. Vieira *et al.* presented a very good survey on sensor nodes in [20].

Colandairaj *et al.* [61] demonstrated that the principles of codesign, the merging of communication technology with control theory, can simultaneously improve both control and
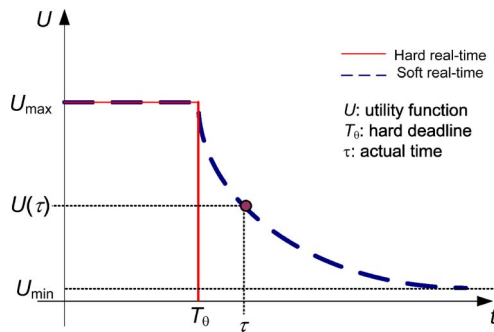
Fig. 3. Utility function for hard and soft real-time applications.

communication performance within an IEEE 802.11b WNCS using sample rate adaptation. Matkurbanov *et al.* [23] presented a survey and analysis of wireless fieldbus with comparison and practical test of recent wireless fieldbus technology.

Overall, the choice of network depends upon the desired application. Today, with the help of technologies like GPS, which is an electronic atlas (Google maps), we are looking at multiagent traffic control in urban areas with efficient vehicle communication [56]. Military, surgical, and other emergency medical applications can use dedicated optical networks to ensure fast speed and reliable data communication. The Internet is the most suitable and inexpensive choice for many applications where the plant and the controller are far away from each other [17]. Every network/communication medium can have a degrading effect on the system performance. Some of them are discussed in further sections.

B. Network Delay Effect

The network can introduce unreliable/nondeterministic levels of service in terms of delays, jitter, and losses [50]. In time-sensitive NCSs, if the delay time exceeds the specified tolerable time limit, the plant or the device can either be damaged or have a degraded performance. Time-sensitive applications can be either hard real time or soft real time. As shown in Fig. 3, in hard real-time systems, the utility function immediately goes to zero as soon as the deadline for the task is reached, and therefore, the task must be completed before the hard deadline. In soft real time, the utility function gradually degrades to $U_{\min}$.

1) Modeling and Analysis of Network Delays: In order to study the network delay effect on NCSs, modeling of the delay and the other network properties, like packet drops and jitter, is important. Network delays are modeled and analyzed in various ways. They can be modeled as a constant delay (timed buffer), an independent random delay, and a delay with known probability distribution governed by the Markov chain model [45]. In 1988, Sato *et al.* [59] explored some techniques for network delay analysis which was based on the fact that, in the network, the information can be efficiently integrated and transported by maximizing the use of the burstiness of the information flow and of the store-and-forward process at the transport nodes. Later, Wu *et al.* [46] modeled and analyzed the stability of NCSs with long random delay. Kamrani and Mehraban [60] modeled end-to-end time delay dynamics for the Internet using system identification tools. In order to minimize the effects

of delay on the performance of the NCS, both accurate delay modeling and, later, delay compensation methods are practiced as discussed further.

2) Delay Compensation: Different mathematical-, heuristic-, and statistical-based approaches are taken for delay compensation in NCSs [9]. Several advanced techniques have been presented in literature that compensate for or alleviate the stochastic network delay, potentially enough to be used in critical real-time applications. The optimal stochastic method approaches the problem as a linear–quadratic–Gaussian (LQG) problem, where the LQG gain matrix is optimally chosen based on the network delay statistics [81]. The queuing/buffering method is a popular method that turns the NCS into a time-invariant system to alleviate the delays [79], [82]. Queuing strategies are proposed by many researchers for coping with the networked delay and packet dropouts for both linear and nonlinear plant. The advantages of this method are the following: 1) no need to redesign the existing predictive controllers; 2) no requirement of clock synchronization; and 3) only slight influence of bad network condition such as package loss. The robust control method considers the delays as multiplicative perturbations on the system and uses robust control to minimize the effect of the perturbations and maintain system performance [80]. This controller does not require *a priori* information about the probability distribution of network delays. In the last decade, some more techniques were proposed such as nonlinear and perturbation theory [29] and sampling time scheduling. Some control techniques are developed for a specific kind of applications. These techniques include wave variables [83] and event-based control. However, applying and implementing these control techniques on existing systems that are extensively being used in industrial plants could be costly, inconvenient, and time consuming. The main reason is that all existing controllers may have to be redesigned, replaced, or reinstalled in order to be used over data networks. Some of these methods also have put some strict assumptions on NCSs, e.g., network time delay is less than the sampling period, NCSs without random network delay, and data transmitted in packets.

In [42], Yue *et al.* considered the problem of the design of robust memoryless H_∞ controllers for uncertain NCSs with the effects of both the network-induced delay and data dropout.

Soucek *et al.* [52] focused on the effect of delay jitter at a fixed mean delay on the QoC. Two sources of delay jitter are identified in EIA-852-based systems: 1) network traffic induced and 2) protocol induced. Zhang *et al.* [47] investigated the problems of stability and stabilization of a class of multimode systems. Choosing the proper Lyapunov–Krasovskii functionals and using a descriptor model transformation of the system, Li *et al.* [44] derived linear matrix inequality (LMI)-based sufficient conditions for stability. Fig. 4 shows a typical NCS model by Tipsuwan and Chow [10] with the time delay.

A gain scheduler middleware (GSM) is developed by Tipsuwan and Chow to alleviate the network time delay effect on the NCS [27] (Fig. 5). A new delay-independent stability condition is presented in no-passive systems in [26]. Xia *et al.* [43] proposed a new control scheme consisting of a control prediction generator and a network delay compensator.
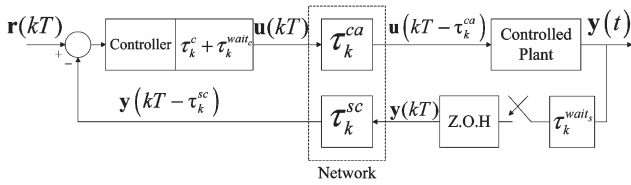
Fig. 4. Block diagram of the NCS plant structure showing the network delays designed by Tipsuwan and Chow in [10].

However, precise delay time models are needed for implementation of the predictive methods. Natori and Ohnishi [51] proposed a time delay compensation method based on the concept of network disturbance and communication disturbance observer. In this method, a delay time model is not needed. Hence, it can flexibly be applied to many kinds of time-delayed systems. Richards and Chow [18] investigated four methods—GSM, optimal stochastic, queuing, and robust control methodology—that alleviate the IP network delays to provide stable real-time control using a case study on a networked dc motor. In [11], Liu *et al.* discussed the design of NCSs with a networked predictive controller in the presence of random network delay in both the forward and feedback channels. Zhang *et al.* [7] represented nonlinear NCSs by a T-S fuzzy model and addressed network delay as well as packet drop issues using robust H_∞ control. Li *et al.* [78] proposed a novel discrete-model switch system for NCSs with time delay and packet drop. With this model, they designed a state-feedback controller for NCSs for asymptotic stability. Network delay compensation thus has been studied in depth, and many solutions, some application-based and some theoretical, are proposed in literature. However, as NCS approaches more and more complex applications and systems, the following research topics have emerged.

C. FTC in NCS

Built-in redundancy improves failure rates, while fault tolerance is implemented to prevent faults from propagating through the system; both are essential elements of a safety critical NCS. Here, some of the important literature related to fault-tolerant control (FTC) in NCSs has been cited.

Patankar presented a model in [69] for a fault-tolerant NCS using time-triggered protocol communication. Huo *et al.* [68] studied scheduling and control codesign for a robust FTC of NCS based on robust H_∞ FTC idea. Wang *et al.* [71] proposed a fault detection approach for NCS, which considers the influence of unknown and random network-induced delay as multiplicative faults. Mendes *et al.* [70] proposed a multiagent platform based on decentralized design and distributed computing for FTC systems. Zhu and Zhou [72] applied a states-observer-based fault detection approach on the uncertain long-time-delay NCS without changing the system construction. A procedure for controlling a system over a network using the concept of an NCS information packet is described by Klinkhieo *et al.* in [73]. This procedure is composed of an augmented vector consisting of control moves and fault flags. The size of this packet is used to define a completely fault-tolerant NCS.

D. Bandwidth Allocation and Scheduling

The rapid growth of traffic induced by Internet services makes the simple overprovisioning of resources uneconomical and hence imposes new requirements on the dimensioning methods. Therefore, the problem of network design with the objective of minimizing the cost and maximizing the service data flow becomes increasingly important. Controlling multicomponent NCS, with the finite amount of bandwidth available, bandwidth should be utilized optimally and efficiently. Max–min fair (MMF) principle is widely considered to help find reasonable bandwidth allocation schemes for competing demands. In more practical cases (nonconvex), a general convex MMF problem approach fails [28].

For NCS stability, it is necessary to find the maximum allowable delay bound (MADB). The network scheduling method to be applied should have a basic sampling time within this MADB while still guaranteeing real-time transmission. In [41], Kim *et al.* proposed a new method to obtain the MADB guaranteeing stability in terms of LMI. The proposed approach differs from the popular queuing analysis as there is no queue for time-critical periodic data. Appropriate techniques for NCS scheduling followed.

1) NCS Scheduling Approaches: Different priority scheduling techniques are used in processors these days such as rate monotonic scheduling (RMS) and deadline monotonic scheduling algorithms by embedded system researchers for parallel processing and multithreading. Initially, network scheduling techniques were derived from these techniques, and later, they took different forms to be compatible with network time delay structures because they differ from micro-/nanosecond time delays observed in microprocessors. Branicky *et al.* [34] studied network issues such as bandwidth, quantization, survivability, and reliability. They applied the RMS algorithm to schedule a set of NCSs. The idea is that, if a set of NCSs cannot be scheduled with the given time constraint when every data packet is guaranteed to be delivered, dropping some percentage of the packets of the faster sampling NCSs can be considered to guarantee stability for the same set of NCSs. Wu *et al.* [35] proposed a distributed dynamic message scheduling method based on deadline of message in order to satisfy timeliness of messages and improve the system's flexibility based on CAN.

There are various resource allocation and scheduling techniques now. Simple queuing methods sample the output of the plant periodically and place the resulting data record into a first-in–first-out queue. However, the sensor sampling period must be larger than the average transmission time interval; otherwise, the queue overflows. Another one is try-one-discard, which does not implement a queue. Rather, it discards the data whenever transmission is not possible, for example, network is unavailable [29]. Martí *et al.* [53] showed that the codesign of adaptive controllers and feedback scheduling policies allows for the optimization of the overall QoC. They described an approach for adaptive controllers for the NCS to overcome some of the previous restrictions by online adapting the control decisions according to the dynamics of both the application and executing through message scheduling. Li and Chow [14] (Fig. 6) proposed sampling rate scheduling to solve the problem
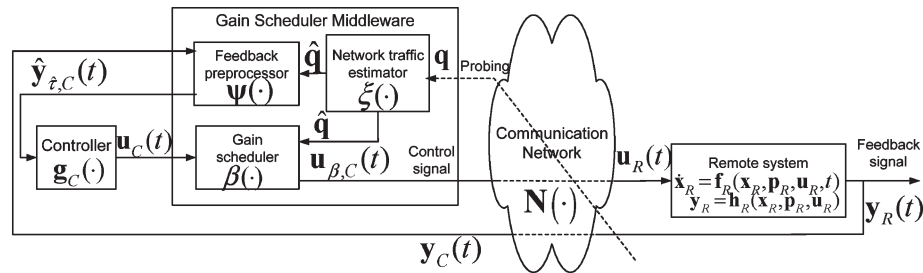
Fig. 5. Block diagram of the GSM module designed by Tipsuwan and Chow [27] for network delay compensation.
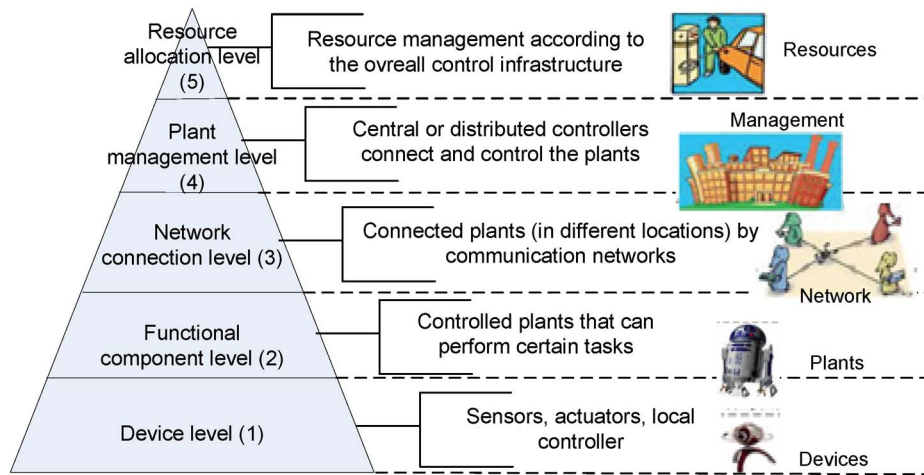

Fig. 6. NCS model representing the resource allocation stages [14].

of signal fidelity and conserve the available data transmission. Al-Hammouri *et al.* [32] proposed an asynchronous, scalable, dynamic, and flexible bandwidth allocation scheme for NCS, formulating the bandwidth allocation as a convex optimization problem in a fully distributed manner.

There are also many tools like Petri-net modeling [16], integer, nonlinear, dynamic programming, AI tools, and genetic algorithms developed for scheduling of NCS. Hong *et al.* [16] scheduled a life science high-throughput platform using timed transition Petri nets and heuristic searching. Martí and Velasco [54] reviewed basic control models for flexible scheduling in real time and built a new model which allowed irregular sampling while still having better schedulability and robustness. Pereira *et al.* [36] dealt with scheduling real-time transmission in a wireless industrial network. They developed a new collision-free wireless medium access protocol (MAC) with static-priority scheduling. Grenier and Navet [75] highlighted a class of online scheduling policies targeted at scheduling frames at the MAC level.

2) DBA: Dynamic bandwidth allocation (DBA) service is used for networks supporting multimedia applications like VoIP, video traffic, and ATM networks. IP over optical network performance can be improved with DBA, depending on the reallocation paradigm and the network topology as shown by Gannett *et al.* [31]. Ethernet-based passive optical network technology is being considered as a promising solution for next-generation broadband access networks due to the convergence of low-cost Ethernet equipment and fiber infrastructures. McGarry *et al.* [30] provided a comprehensive survey of DBA schemes and methods.

State estimation under rate constraint is also a research problem related to finite bandwidth. Minero *et al.* [85] present a data rate theorem for stabilization of a linear discrete-time dynamical system with arbitrarily large disturbances, over a rate-limited time-varying communication channel. Li and AlRegib [86] considered the distributed parameter estimation in wireless sensor networks, where a total bit rate constraint is imposed. They studied the optimal tradeoff between the number of active sensors and the quantization bit rate to minimize the estimation mean-square error. Soglo and Yang [87] proposed a combination of compensation and estimation methods for delays and packet dropouts at the controller unit to improve the performance of the NCS. There is a lot of literature available for motion estimation under rate constraint in video and image processing as well.

E. Network Security in NCS

Any network medium, particularly wireless medium, is susceptible to easy intercepting. Research in NCS was initiated from the concern for safety and convenience in hazardous environments such as nuclear reactor power plants, space projects, nursing homes, military applications, etc. In all these applications, security is of the utmost concern. The British Columbia Institute of Technology Industrial Security Incident Database contains information regarding security-related attacks on process control and industrial networked systems. Dzung *et al.* [39] gave an overview of IT security issues in industrial automation based on open communication systems and also explained various countermeasures.
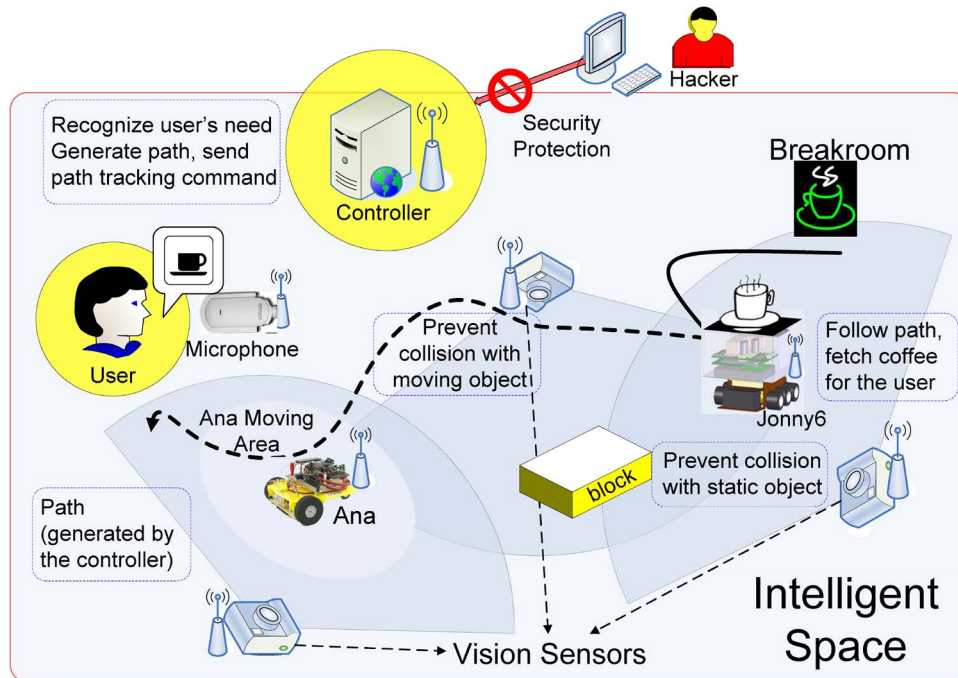
Fig. 7.   Conceptual diagram of iSpace—another example/application of NCS as presented in [48].

Most NCSs are vulnerable to network attacks nowadays, so there is a growing demand of efficient and scalable intrusion detection systems (IDS). Tsang and Kwong [37] proposed an efficient and biologically inspired learning model for multiagent IDS utilized in the network infrastructures of industrial plants. Creery and Byres [38] presented methods to determine and reduce the vulnerability of NCS to unintended and malicious intrusions for an industrial plant. Xu *et al.* [12] developed a core architecture to address the collaborative control issues of distributed device networks under open and dynamic environments by adopting policy-based network security technologies and XML processing technologies. Gupta *et al.* [48] and Gupta and Chow [49] characterized the WNCS application on the basis of security effect on NCS performance to show this tradeoff for an NCS path-tracking application. However, NCS with security from the control system's perspective is in infancy. There is a large scope of research considering the practicality of NCS in any critical application. The same goes for integration of components. This is another issue when it comes to actual implementation of NCSs on broader scale.

F. Integration of Components in NCS

After discussing the individual modules involved in NCS and possible issues related to control systems and network structure, now, the integration of components to achieve the final goal is the key point. These modules perform independent tasks, yet together, they make one large distributed system. Thus, it is evident that, to improve the efficiency of a network control integrated system, not only each integrated module has to be improved but also the efficiency of the data interface between different modules has to be focused.

1) Techniques and Operating Systems Available for Successful and Reconfigurable Integration: A well-designed software architectural framework and a middleware are critical for the widespread deployment and proliferation of NCS. Furthermore, 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, the suitability of the communication environment and command modules should also be taken into consideration.

Baliga and Kumar [24] developed a list of key requirement for such middleware and presented Etherware, which is a message-oriented component middleware for NCS. Gupta *et al.* [5] examined the practical aspects of designing and building an NCS that uses Internet as a communication medium. They worked on a multisensor network-controlled integrated navigation system for multirobots, demonstrating the concept of intelligent space [5] (Fig. 7).

Tisdale *et al.* [25] also developed a software architecture for autonomous vision-based navigation, obstacle avoidance, and convoy tracking for the Berkeley unmanned aerial vehicle. Pratl *et al.* [76] introduced an NCS model based on bionic principles to process information from a large number of diverse sensors using multilevel symbolization providing the ability to adapt to changing sensor inputs in an intelligent way. Garcia *et al.* [4] developed a highly integrated control and programming platform named Motronic which composes of a set of dynamically reconfigurable local controller nodes, a graphical programming environment, a remote supervision and control system, and a fault-tolerant fiber optical network. Motronic is currently being applied in the integrated control of large production plants and in energy and power management industries.

In the case of NCS in automotive industry, 1) for ECUs, there should be a well-defined software integration process that satisfies all key requirements of automotive manufacturers; 2) the choice of the degree of decentralization of the architecture has become a crucial issue in automotive electronics. OSEK is a real-time operating system, created as a joint project in the German automotive industry in 1993, to be used in automotive applications. The French car manufacturers PSA and Renault joined OSEK in 1994, introducing their vehicle distributed excutive approach. This OS serves as a basis for the controlled real-time execution of concurrent applications with various networking provisions. There have been many more OS and middlewares such as AlphaOS and AUTOSAR [66]. Di Natale [65] and Kanajan *et al.* [64] demonstrated how a rigorous methodology and the Metropolis framework can be used to find the balance between centralized and decentralized architectures.

IV. CONCLUSION AND FUTURE RESEARCH

In this paper, the NCS and its different forms are introduced. NCSs have been popular and widely applied for many years because of their numerous advantages and widespread applications. This paper identified some of the main research topics related to NCS. Some of them have been analyzed since the advent of NCS such as network delay compensation and resource allocation. The ones which came into focus later to improve NCS are scheduling, network security with NCS, fault tolerance, etc., which are also studied in this paper.

Although NCS has been a very promising research topic for decades, there are challenging problems and unsolved problems to be considered for future research.

With increasing real-life applications for NCS, the real-time secured control is an important issue. This gives rise to a real-time optimization problem and security threat modeling requirement in NCS. Designing an FTC system for a large-scale complex NCS is still very difficult due to the large number of sensors and actuators spatially distributed on a network.

Modifying the control part of the system depending upon the network delay behavior is one way of dealing with the problem. On the other hand, researchers in the field of wireless networking and communication are working to build new protocols which will give the flexibility to the system and make it time independent [33]. Radcliffe and Yu [55] developed a new intermicroprocessor communication time-independent asynchronous protocol (TIA) which will be useful for a variety of cost-sensitive applications. However, they raise a question whether this TIA will also be useful for communications other than interprocessor communication as this might be useful for industrial and commercial applications [77].

With the help of technologies like GPS, which is an electronic atlas (Google maps), we are looking at multiagent traffic control [40] in urban areas with efficient vehicle communication [56]. However, the problem is not only restricted to just vehicular communication but also includes correct data estimation, data fusion in real time to make robust decisions.

Due to the vast amount of citations in the NCS and the limited pages of this paper, the authors apologize for not being able to list all the related citations in this paper.

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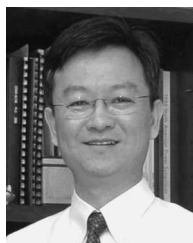
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