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Control and Communication Synthesis in Networked Control Systems

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Abstract- **Currently, researchers from varied disciplines are interested in both commercial potentials and technological challenges introduced by networked control systems (NCS), since NCS provide flexible sensory information processing and distributed actuator manipulating. Although the techniques for building NCS accelerate notably in industrial and university research centers during the last few years, many fundamental questions regarding the co-design of control and communication remain to be thoroughly answered. This paper summarizes some recent developments in this field, addresses several key findings and trends, and also discusses some interesting problems.**

***Index Terms*—Computer network, networked control systems (NCS), agent-based control.**

1. INTRODUCTION

An important trend in the recent control research and applications is to integrate some geographically distributed sensory, actuator and control devices/components through communications networks to achieve distributed sensing, computing, executing and higher-level decision-making [1]-[7], which in a whole builds the so called Networked Control Systems (NCS). The rise of NCS stems from several aspects. First, the direct wirings now become troublesome and impractical, because the complexity of the control systems increases notably with their scales.

Second, quickly developing communication techniques can provide flexible system installation, manipulation and expansion with low costs, which significantly increases reliability and efficiency.

Third, the mobile controllers exceed the stationary controllers in more and more areas, especially when information and operations are locally unavailable. A typical example is the NCS used in RoboCup to link and synchronize a team of fully autonomous humanoid robots. Networks (usually wireless) are now viewed as the essential links for these novel mobile controllers world-widely.

All these benefits had prompted the researchers to put increasing efforts in this field. As a result, techniques in building NCS accelerate notably in the last 20 years. However, several important problems (i.e. how network communications affect the stability/performance of NCS and how we can deal with it) arose and required deliberate discussions, despite the amble results achieved.

In the traditional control systems, information from the sensors is assumed to be instantaneously available for the controller and control commands are assumed to be instantaneously delivered to the actuator. But in NCS, no matter what networks are used, several side effects will be introduced into the control loops during communication. Regardless of the network architecture/medium/protocol, the outcome of a NCS is affected by but not limited to the following factors:

1) sampling rate constraints and resulting distortions of the signals from the sensors or to the actuators;
2) network capacity for communications;
3) disturbances introduced in communications;
4) time delay in the measurement and control loops;
5) data loss or package drop if using package-based NCS. In wireless network situations, data packets may arrive at variable times, not necessarily in order, and sometimes lose at all.

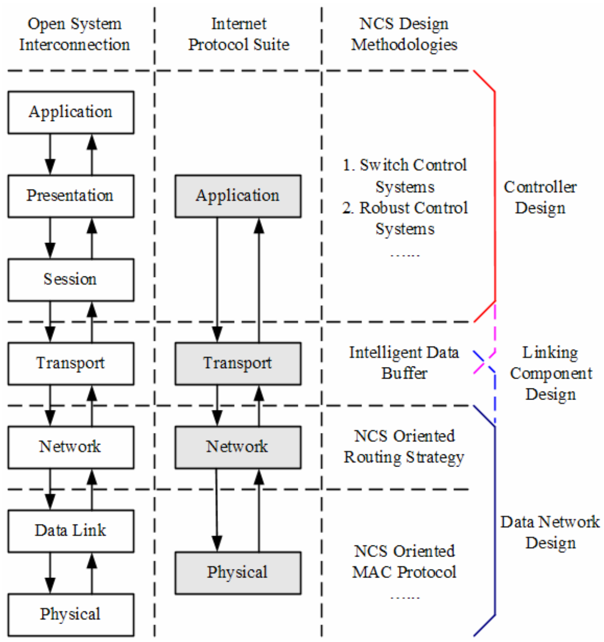

Fig.1. Division of NCS design methodologies according to OSI 7-layer protocol and Internet protocol suite.

Most recent approaches to handle these problems can be divided into two implicitly interlaced directions according to their focuses:

1) to build good communication networks in which the above side effects are trivial or can be neglected;

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2) to design intelligent controllers which can tolerate the above side effects to a certain degree.

More precisely, varied studies can be also categorized regarding their working levels of the overall network communications as shown in Fig.1.

However, recent achievements indicated that controller design and communication design problems should be solved simultaneously. To provide a better understanding of the research activities, this paper provides an classified overview of the issues central to recent practices. Some interesting questions that are yet to be investigated are also discussed, since the answers may be quite helpful for both theoretical and practical use.

2. CONTROL-ORIENTED COMMUNICATION DESIGN IN NCS

In general, the following five objectives need to be considered when building a communication network for NCS:

1) system performance, i.e. fast response, low data loss ratio, big allowable bandwidth, high signal-to-noise ratio (SNR);
2) system reliability in terms of failure possibility and resiliency when failure occurs;
3) system security, especially for wireless NCS [89]-[90];
4) system flexibility, i.e. plug-and-play installation/ un-installation, on-demand bandwidth reservation and smart resources managements;
5) provide the characterization of channels in forms which are more meaningful for control applications.

Particularly, the first objective must be reached, since control-oriented networks are usually assumed to support large data flow, high data peaks and in-frequent bursty transmissions for the real-time/time-critical applications. However in practices, constraints can arise from several sources, i.e. technique limitations and cost considerations.

2.1 NCS Oriented MAC Protocols Design

A well known constraint for NCS is medium access, which implies that the allowed maximum number of simultaneous medium access channels is much smaller than the number of sensors and actuators in the system. Therefore, a control network should adopt appropriate scheduling transferring algorithms to reduce the time delay which highly influence the system performance.

One straightforward solution is to let the medium access of different elements follow a pre-defined communication sequence order [8]-[10]. This scheduling strategy is often called 'static' scheduling, since the order of these sequences will not be changed. How to find the best static signal sequence is studied in [11]-[12]. But if given a periodic communication sequence, a stabilizing feedback gain cannot be analytically solved and the search procedure of its existence has been proved to be NP-hard [13], too. To conquer this problem, some 'dynamic' scheduling strategies were proposed using the feedback-based arbitration policies, which harmonically increase real-time packets and decrease the non-real-time ones to avoid congestion and improve throughput.

The so called 'clear largest buffer' policy was introduced in [14] and modified as the 'CLS-ε' policy in [15]-[16]. Their basic idea is to let the subsystems whose states are furthest from the origin win the medium access, and redirect the medium access when the norm of the state of that subsystem is driven to a small positive real number ε. It was shown that NCS can be asymptotically stabilized by gradually decreasing ε. However, it is normally hard to estimate the allowable range of ε.

Another protocol called Maximum Error First, Try-Once-Discard (MEF-TOD) were proposed in [17]-[19] using dynamic data queues dispensing. The policy is: i) at any time, the input or output with the greatest weighted error from its most recently transmitted value win the access of the medium; ii) if an input or output fails to win the competition for the network access, it discards its current value. Suppose that the maximum interval for an element between its two successful transmissions is bounded by a small number called Maximum Allowable Transfer Interval (MATI), the asymptotically stability of the NCS can then be checked using Bellman-Gronwall Lemma. Vice verse, when MATI is found via Bellman-Gronwall Lemma, the design specification of the network is determined. However, it was pointed out in [17] that this bound obtained is normally conservative because of the conservativeness of Bellman-Gronwall Lemma. Further testing and modifications result of TOD can also be found in [20]-[21].

The above discussions assumed that special protocols can be employed; but in most real applications, one of the common protocols (i.e. Lon-Works, CAN, ControlNet, DeviceNet, TTCAN) will be chosen because of time and cost considerations. In these protocols, elements are competing to win the access of the network so that the accessing time is unavoidably random, although this kind of randomness can usually be well estimated. This raises an interesting question which yet to be answered

Question 1: how to analytically take account of the accessing time/order randomness in controller performance design?

Although amble simulation or practice results had been provided, theoretical conclusions are still meaningful and necessary.

2.2 NCS Oriented MAC Protocols Design

In control applications using fieldbus, routing is not a big problem. A typical solution is the not so complicated Smart Multi-station Access Units (SMAU) which work as the hubs in the token ring networks.

But in mobile agent-type NCS, routing becomes an important but hard task. If comparing to the celebrated sensor network research, it is easy to find that NCS research has many overlapped problems, such as energy constraints [22]-[24]. An element may have limited power supply, and recharge of power is often impractical and time consuming. Energy efficiency is thus crucial in sustaining network functionalities and extending system lifetime. Because wireless communication contributes a major part to energy consumption, some different routing protocols including hierarchical protocols and location based protocols were proposed for saving energy. But this leads to another question below. Noticing the potential great benefits, far more efforts are expected to make into this direction in the near future.

Question 2: how to find an appropriate compromising plan which satisfies control and some other requirements, e.g. use the smallest energy?

3. Linking Components Design in NCS

A linking layer (intelligent data buffer) between networks and controllers (see Fig.1 and Fig.2) is essential for many NCS, because:

1) the command issued by the controller may wait to access the channel. To avoid data loss, a certain basic output buffer is required;

2) the measurement signal can be lost, arrive at a wrong time (usually lagged) or in wrong order, etc. Thus, an intelligent input buffer is needed, see Fig.3.

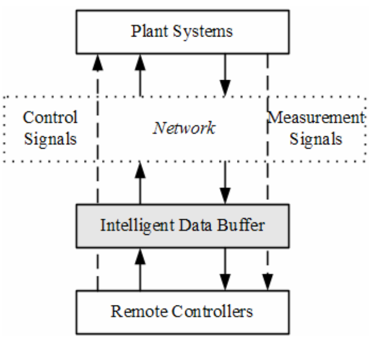

Fig.2. NCS with intelligent data buffer.

The correction of data's time coordinates is quite straightforward if both occurring and transferring time-stamps of the data are available. But the imputation of the data missed usually requires use of *a priori* knowledge. For example, maximum entropy spectral, neural networks and ARMA models are often employed to "learn" the data patterns from previously collected data and then estimate/ interpolate the lost data points based on the known ones [25]. But it seems there is not a unified solution for various control applications.

Besides, the data buffer needs to carry out the coding/ decoding task, which is known since Shannon [26]-[27] to relate with channel capacity that will be discussed in the following Section IV. An important but open question is

Question 3: is it possible and how to enable the existing controllers for NCS usage via minimum communication supports?

Some attempts were given in [28]-[29]. But it is clear that further studies are still in bad need.

Fig.3. Intelligent input data buffering, which correct data's time coordinates and impute the missing data.

4. Controller Design in NCS with Regard to Communication Constraints

4.1 Channel Capacity and Control in NCS

Network communications take away lots of simplifying but workable assumptions that control theorists have made till now. A newly emerged problem is whether there is sufficient communication band-width, or plainly bit-rates, to guarantee the closed-loop system's observability and stability, since the capacity of a digital link is usually limited.

In [30]-[31], a new concept, finitely recursive coder-estimator sequence, was introduced to analyze the magnitude bounded disturbance of estimation caused by the length-limit effect. It first studies under what condition, there exists a sphere S centered at the origin in R^d so that the corresponding coding and feedback control laws can ensure all trajectories starting from an open neighborhood of the center remain in S. Thus, a weaker stability concept called 'containability', which is closely related to the concept of practical stability and uniform practical stability, was defined to study the close-loop stability. Based on it, the relation between the final offset bound, time delay and encoding word length can then be determined.

The idea of 'containability' was strictly analyzed in many following literatures. For instance, four kinds of channels: noiseless digital channel, delayed noiseless digital channel, erasure channel, and memoryless Gaussian channel were examined in [32]-[34]. A framework was generalized by applying traditional information theoretic tools of both source coding and channel coding to the problem.

Suppose the discrete-time linear NCS can be written as

$$X(t+1) = AX(t) + BU(t) \quad (1)$$

$$Y(t) = CX(t) \quad (2)$$

where $X(t)$ is a R^d state process, $Y(t)$ is a R^l observation process, $U(t)$ is a R^m control process. A, B and C are the corresponding system matrixes with appropriate dimensions.

A simple but powerful result was proved as

Theorem 1. A necessary condition on the rate for asymptotic observability and asymptotic stability is

$$R \geq \sum_{\lambda(A)} \max\{0, \log|\lambda(A)|\} \quad (3)$$

where $\lambda(A)$ represent the eigenvalues of the matrix A.

There were some improvements of estimating rate bound R by further analyzing the eigenvalue structure of A. In [35]-[38], it was further pointed out that

Theorem 2. Any unstable discrete time linear plant affected by arbitrarily small external disturbances with probability 1 can be neither stabilized nor observed over any erasure channel with nonzero erasure probability.

Different from such a train of thought, Topological Feedback Entropy (TFE) based approach is another interesting way for NCS stability analysis [39]-[41]. Topological entropy was originally proposed to define entropy for completely deterministic nonlinear maps [42], which applies to continuous maps on compact topological spaces. As briefly summarized in [40], "*the idea behind this definition is to first fix an open cover for the space, 'through' which each iteration of the map is observed.*"

TFE is an extension of the normal topological entropy to maps on non-compact spaces with inputs, but there is a significant difference in interpretation. It had been proven that by a causal coding and control law belonging to a general class, to characterize the smallest possible data rate equals to permit a specified compact set to be made invariant. In this context, the infimum data rate is precisely equal to the plant's intrinsic information rate measured by its topological feedback entropy.

Moreover, an important result is the explored connections between the entropy of a dynamical system and Bode's sensitivity integral [43], which can be finally examined as the right half-plane poles and zeros (RHS) and design tradeoffs in feedback systems. It was shown in [44]-[45] that the RHS of Ineq.(1) is similar to the expressions for the Kolmogorov-Sinai and topological entropy rates of linear maps. The only difference is that such notions are defined for open-loop systems, while the infimum stabilizing data rate is a closed-loop concept. But indeed, it is possible to rigorously define TFE describing the rate where the plant generates information in a stable feedback loop, i.e. in [40].

By taking appropriate limits, a local TFE at a fixed point can then be defined and shown to coincide with the RHS of Ineq.(1). From this viewpoint, exponential stability is possible if and only if the data rate of the channel exceeds the local TFE at the desired set-point. These two threads of study can be taken as different interpretations that parallel Shannon's source coding theorem; Fig.4.

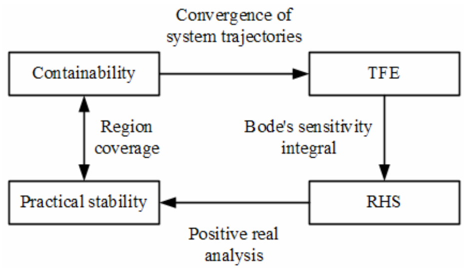

Fig.4. Relations of different approaches considering NCS' capacity problem.

4.2 Quantization and Control in NCS

Quantization has been discussed in the context of digital control and signal processing for over thirty years. It is tightly connected with the buffering and channel capacity problems that have been discussed above.

Typically, quantizers round off the signals uniformly with a constant step size. As discussed in Section III, intelligent data buffer will be used to correct the data's time coordinates in this cases.

The resulted quantization error is often modeled as uniform and white noise. It was shown that the above formulation (1)-(2) allows directly analyzing the systems with process disturbances and different information patterns. For instance, stochastic Lyapunov methods had been employed in [46]-[48] to study the systems with stochastic disturbances. Optimal controller design methods especially linear quadratic controller (LQC) designs under rate-constrained channels are also discussed in [49]-[51]. On the other side, it was also shown that complicated behaviors including limit cycle and strange attractors can be observed even in a simple feedback loop.

Different from the above deterministic treatments of quantizers, many recent approaches follow an influential method initialed in [52], which introduces time-varying quantizers to possibly decrease the number of bits. Follows the concept of 'containability' given in Section IV.1, the basic idea here is to use cells to cover only the necessary region in the state space at the time; thus use fewer cells in the quantizer might reduce the data rate. Usually, a non-uniform quantizer is formulated as the result of an optimization problem with coding and time delay explicitly taken into account. Some detailed discussions can be found in [53]-[58].

4.3 Time Delay and Control in NCS

One major challenge for NCS design is the network-induced delay effect in the control loop. Some delays, i.e.

the transmission time delay that it takes for a transmitter to send out data, are constant. Others including sequencing time caused by the waiting consequence of medium access are naturally time-varying and sometimes hard to estimate.

A simple approach is to examine the longest time delay that can be tolerated if the controller is given. For instance, one simple method is to analyze the maximum allowable frequency-domain shift of the systems' eigenvalues caused by time delay [59]-[60]. Similarly in time-domain, the Maximum Allowable Transfer Interval (MATI) was proposed in [61]-[62] to examine the maximum allowable time delay for linear NCS. However, this usually leads to time-consuming search-test procedure.

Another frequently applied technology is robust control. In the last twenty years, Lyapunov-Krasovskii (L-K) and Lyapunov-Razumikhin (L-R) functions are widely used to analyze time-delay independent and time-delay dependent stability of systems with varied but bounded time delay [63]-[68]. But complete L-K functional normally yields infinite dimensional LMI condition sets which are difficult to verify algorithmically with the current tools. One solving method is to use the approximate complete L-K functional, i.e. via the discretization scheme or the sum of squares decomposition scheme. Other methods include finding incomplete but less conservative L-K functional [69]-[71]. On the other hand, L-R functional is usually used to study the systems with a large class of time-varying delays; and the delay-dependent stability criteria can similarly be derived based on model transformation. But this often leads to solving Bilinear Matrix Inequality (BMI) problems [67].

4.4 Other Problems

Because of high data rates and computational loads, packets sent across the network are not always received. Thus, several probabilistic models for packet dropping were proposed for studying erasure channels and bounded variance stabilization conditions [72]-[76]. We believe more reports using similar techniques will be seen soon.

Most the NCS discussed in the paper are assumed to be triggered by internal "time". But hybrid/switch control NCS that are driven by external "events" are gaining boosting interests now [77]. Obviously, it is harder to investigate the stability of such NCS.

NCS Control synthesis which simultaneously considers network delay, capacity constraints and/or packet loss received increasing attentions recently [78]. However, further discussions are needed in this direction.

5. Agent-Based Control in NCS

5.1 Remote Supervision

Traditionally, NCS are only referred to direct type distributed control loops shown in Fig.2. But agent-based NCS attract increasing interests recently [79]-[83]. Fig.5 below illustrates a server-local type agent-based NCS that contains a local controller which is linked to the plant systems straightforwardly and a remote server via the networks. The local controller is independent of executing some basic control programs. Due to cost considerations and hardware limitations, these basic operations are relatively simple, which can only lead to suboptimal control results. But the performance of this local controller could be monitored and periodically/aperiodically tuned by the remote server based on the collected information.

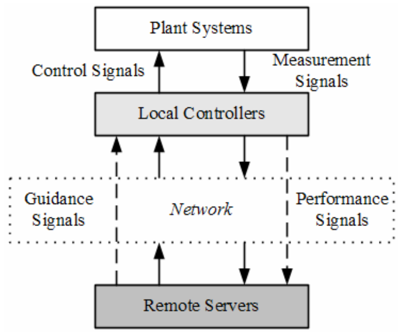

Fig.5. Diagram of agent-based NCS.

Usually, the remote server will passively receive the sampled inputs and outputs of the local systems, evaluate their performance and determine how to tune the local controllers. Since all the tedious controller optimization tasks are moved from the local controller to remote server, the control devices can be much simplified, which greatly helps to reduce the costs and fault liability of the systems. This trend of development brings promising prospects to future smart electronic applications, because it allows easier failure monitoring, upgrading, and efficiency maintaining.

However, the local controller needs to simultaneously carry out control actions and response for the newly gotten configuration parameters or updated algorithms from the remote sever. These two operations normally interfere with each other. Thus come the following coupled questions remaining to be answered

Question 4: how to solve this dilemma in a time critical application?

Question 5: how to convey the high-level guidance information reliably (secretly) and efficiently?

5.2 Time Delay and Control in Agent-Based NCS

Cooperation among varied agent-based NCS, especially mobile agents, is another hot topic during the last decade. Its main objective is to synchronize the behaviors of varied NCS to achieve certain goals, i.e. keeping formation [84], collecting distributed information [85], avoiding traffic hazards [86] via networked negotiation and coordination. Results indicate that delay might greatly change the collaborative behavior of the overall system and may even lead to chaos. The important and attractive question below is still open despite the tremendous results achieved in the last decade.

Question 6: to what degree time delay is not a trivial factor and what kind of nuances the overall system may yield regarding the variations of time delay?

6. Conclusions

This survey systematically reviews the fundamentals and some recent results of NCS. The newly established synthesis of communication, control as well as information processing methods implicates that not only the data is delivered via the networks but also the "intelligence", particularly knowledge, is shared and evolutes over the networks.

Due to the length limit, some research directions are regretfully neglected, for example:

1) supporting techniques for network constructing, e.g. how to develop (embedded) operation systems for real-time/time-critical NCS application [87]-[88];

2) security problems, the existence and importance of which is undeniable [89]-[90];

3) communication network fault detection and fault tolerant control techniques, which are receiving increasing attentions;

4) human-in-loop NCS which are crucial to certain types of tele-operations. Due to its importance, more results are expected to be presented in this area in the coming future [91]-[93].

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