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Trends in Networked Control Systems

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Abstract: This report presents the major contributions and the possible future challenges in the emerging area of Networked Control Systems. Activities in this field can be categorized into control of networks, control over networks, and multi-agent systems. Control of networks is mainly concerned with providing a certain level of performance to a network data flow, while achieving efficient and fair utilization of network resources. Control over networks deals with the design of feedback strategies adapted to control systems in which control data is exchanged through unreliable communication links. Multi-agent systems deals with the study of how network architecture and interactions between network components influence global control goals. More precisely the problem here is to understand how local laws describing the behavior of the individual agents influence the global behavior of the networked system.

1. INTRODUCTION

Many infrastructures and service systems of the present-day society can naturally be described as networks of a huge number of simple interacting units. Examples coming from the technological fields include transportation networks, power grids, water distribution networks, telephone networks and the Internet. Additional relevant examples can be found in other areas, e.g., the global financial network, genetic expression networks, ecological networks, social networks and so on.

Limiting our attention to the engineering field, the reasons of the technological success of this design paradigm is manifold. The main winning features of networked structured systems come from their low cost, their flexibility and easy re-configurability, their natural reliability and robustness to failure, and their adaptation capability. Some of these characteristics, though quite clearly recognizable from natural networked system examples listed above, are still not completely understood and so their engineering implementation is still to come. This is mainly due to the fact that it is still not completely clear how the rules describing the local interactions and the network structure influence the properties of the global emerging system. For this reason it is still a difficult task to design these local rules and the network architecture in order to obtain some prescribed global performance. However, it is clear both in the academia and in the industry that this paradigm will play a central role in the near future.

Currently engineers, and control engineers in particular, have to cope with many new problems arising from networked systems while designing complex networked systems. In fact, thanks to the low cost and the flexibility of communication networks (Ethernet, Wi-Fi, the Internet, CAN...), these are widely used in industrial control systems (remote control, wireless sensors, collaborative systems, embedded systems...). For instance, the web technology on the Internet today appears as a natural, inexpensive way to ensure the communication link in remotely controlled systems. On the other hand, at the moment the engineer has few tools which allow him/her to exploit this architecture and these tools are mainly concerned with the negative impact caused by the very nature of the communication networks (delays, data loss, data quantization, asynchronous sampling,...).

For these reasons we expect that the impact of networks in control is only going to increase in future years. Moreover, the problems arising in this context are rather novel, especially because of their interdisciplinary nature. In fact, their study requires both to have a deep knowledge in automatic control, computer science and communication networks, and to capture the interplay between these disciplines.

Activities in the area of Networked Systems can be categorized into three major fields:

(1) Control of networks,
(2) Control over networks, and
(3) Multi-agent systems.

Control of networks is mainly concerned with providing a certain level of performance to a network data flow, while achieving efficient and fair utilization of network resources.

Control over networks deals with the design of feedback strategies adapted to control systems in which control data is exchanged through unreliable communication links.

Multi-agent systems deals with the study of how network architecture and interactions between network components influence global control goals. More precisely the problem here is to understand how local laws describing the behavior of the individual agents influence the global behavior of the networked system.

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2. CURRENT KEY PROBLEMS

2.1 Control of networks

Control-based approaches in communication networks is a very large research field. In order to be able to control the network performance, it is necessary to measure and modify the network parameters. The current layered communication architecture is not ideal for cross-layer designs, where information from the lower layers must be made available at the application layer and where the application layer must be able to modify the behavior of the lower layer protocols dynamically. Hence, new protocols and protocol models are needed.

In the area of control of networks, major problems of interest are call admission, scheduling, routing, flow control, power control, and various other resource allocation problems. The objective is to provide quality of service (QoS), while achieving efficient and fair utilization of network resources.

2.2 Control over networks

Sensors and actuators network is a control architecture in which sensors, actuators and the computing units, where the control algorithms run, are remotely positioned and communicate with each other through a communication network. This scenario occurs in the field of embedded control systems, in large manufacturing systems, in automotive systems, etc. The advantages of this architecture have been mentioned above. However, there are also some drawbacks due to the characteristic features of the communication method adopted, namely there is the need to deal with the following problems:

(1) Data transmission through communication network unavoidably introduces **time delays** in the control loops; see Richard and Divoux (2007); Canudas de Wit (2006).
(2) Data traffic congestion, data collision or interference can cause **packet loss**.
(3) In networked control systems, communication occurs through digital channels with **finite capacity**.
(4) In control over networks it is important to evaluate the **influence of the QoS** provided by the network on the performance of the control. The characteristics of the QoS are mainly determined by the delays in the message transfer, the message losses and the message integrity.
(5) In case of energy consumption limitations, it may be convenient to adopt an **Event based control** strategy according to which the sensor does not communicate and the actuator does not act until some undesired event occurs.
(6) While using wireless communication networks, much attention has to be devoted to the **security** issues; see Baras (2007).

2.3 Multiagent systems

The research in this field can be categorized into two areas. The first area deals with the design of distributed estimation techniques which can be applied in the framework of the sensor networks technology. Since collecting measurements from distributed wireless sensors nodes at a single location for on-line data processing may not be feasible due to several reasons, there is a growing need for in-network data processing tools and algorithms that provide high performance in terms of online estimation. These algorithms have to reduce the communication load among all sensor nodes, to be robust to node failures and packet losses, and to be suitable for distributed control applications.

The second area of active research deals with the control of mobile autonomous robots. Groups of autonomous agents with computing, communication, and mobility capabilities are expected to become economically feasible and perform a variety of spatially distributed sensing tasks, such as search and rescue, surveillance, environmental monitoring, and exploration. As examples of motion coordination problems, teams of mobile autonomous agents require the ability to cover a region of interest, to assume a specified pattern, to rendezvous at a common point, or to move in a synchronized manner as in flocking behaviors.

3. RECENT MAJOR ACCOMPLISHMENTS, TRENDS

3.1 Control of networks

The success of the Internet as a worldwide information network can be attributed to the feedback mechanisms that control the data transfer in the transport layer of the Internet Protocol (IP) stack. The tremendous complexity of the Internet makes it extremely difficult to be modeled and analyzed, and it has been questioned whether mathematical theory can offer any major improvements in this area. Recently, however, significant progress in the theoretical understanding of network congestion control has been made following the seminal work by Kelly and co-workers; see Kelly et al. (1998). By explicitly modeling the congestion measure signal fed back to the sources, and by posing the network flow control as an optimization problem where the objective is to maximize the total source utility, it is shown that the rate control problem can be solved in a completely decentralized manner; see Kelly et al. (1998); Low and Lapsley (1999). To ensure that the system will reach and maintain a favorable equilibrium, it is important to assess the dynamical properties, such as stability and convergence, of the schemes. The above results ignored the effect of network delay, and assumed that price information is available instantaneously at the source, that the sources take immediate action, and that the new rates affect the link prices instantaneously. However, stability of the protocols in equilibrium depends critically on the feedback delay and on the interactions between the protocol implementations and the network dynamics.

Some of the recent accomplishments in the area of congestion control include development of mathematical models for flow control under various Internet protocols ; see Mascolo (1999); Kelly (2001); Hollot et al. (2002); Jacobsson et al. (2006); Deb and Srikant (2006). The importance of accurate fluid flow models for analysis and design has been illustrated; see Tang et al. (2007). Scalable and distributed optimization algorithms have been developed for these control systems; see Paganini et al. (2005); Mo and

Walrand (2000); Su et al. (2000); Lestas and Vinnicombe (2006, 2007); Pavel (2005); Basar and Srikant (2002); Altman et al. (2002); Alpcan et al. (2005). Effects of time delays and nonlinearities in the network flow models have also been considered recently; see Alpcan and Basar (2005); Fan et al. (2004, 2006); Quet and Ozbay (2004); Yan et al. (2005); Unal et al. (2006); Han et al. (2006); Ying et al. (2006).

Wireless networks are especially interesting from a resource control point of view. Whereas the link capacities in wireline networks are fixed, the capacities of wireless links can be adjusted by the allocation of communication resources, such as transmit powers, bandwidths, or time-slot fractions, to different links. Adjusting the resource allocation changes the link capacities, influences the optimal routing of data flows, and alters the total utility of the network. Hence, optimal network operation can only be achieved by coordinating the operation across the networking stack. This is often referred to as cross-layer optimization. Congestion control and resource allocation for wireless networks are of growing importance; see Abate et al. (2006); Zheng and Nelson (2007); Alpcan et al. (2006b,a); Acemoglu et al. (2004); Musacchio and Walrand (2006); Ying et al. (2007).

3.2 Control over networks

While many contributions were devoted to the design of networked control systems considering delays, data loss and quantization, little attention has still been devoted on event based design Astrom and Bernhardsson (2002); de Wit et al. (2007) and on security issues Baras (2007) arising in this framework.

Delays
Considering the delays caused by communication networks, the mainstream research has been devoted to the design of control/observation algorithms that can stand the delay variations (jitter phenomenon) and their unpredictability. Both are sources of problems when trying to apply the classical, predictor-based control laws Richard (2003). Several works on tele-operation (two-actors situations) introduced the question of transmission delays, first, in the *constant case* Azorin et al. (2003), Fattouh and Sename (2003), Garcia et al. (2000). In the more realistic case of *variable delays*, Witrant et al. (2003) generalized the predictor techniques, by assuming that a dynamical ordinary differential equation model of the delay is available. This is realistic only in the case of a single-owner Ethernet network. In the other cases, a possible solution consists in introducing an input buffer. This technique makes the delay constant, at the price of a lower performance Seuret et al. (2006). Another origin of variable delays in network implementation is due to the time-sampling effect. Following the lines of Fridman et al. (2004), Yu et al. (2004) one can see time-sampling as source of an additional, variable delay Seuret et al. (2006), generally, due to the computer architecture and operating system.

Another approach consists in combining robust control theory and network calculus theory. First, by network calculus theory it is possible to estimate a bound of the end-to-end delays by taking into account the whole network properties. These delays are then translated into uncertainties useful for robust control synthesis Georges et al. (2006). Extension of this work is also related to the control of networks. The solution proposed in Diouri et al. (2007) consists in defining packets scheduling algorithms inside the network devices in order to optimize the quality of service and hence to reduce the effect of the network on the robust controller.

Data loss
The state of the art on design control systems that take into account the effects of packet loss and packet delay in networked control systems have been surveyed by Hespanha (2007) and Hespanha et al. (2007). In particular, Sinopoli et al. (2004) considered the effect of Bernoulli packet loss between the sensor and the estimator in optimal estimation. This work has been further extended to include both packet loss and random delay in Schenato (2006) and smart sensors in Gupta et al. (2005). More interesting is the scenario of packet loss between the controller and the actuator, because the separation principle can be applied only for TCP-like communication protocols where packet loss acknowledgment is available to the controller, while for UDP-like communication protocols the separation principle does not apply; see Schenato et al. (2007), Imer et al. (2006). In this scenario for which standard controller design tools cannot be applied, one of most promising and effective approaches is to design static linear controllers and filters by modeling packet loss and stochastic uncertainty, since it can be recast as convex optimization problem, as shown in Elia and Eisembeis (2004). Note that in some situations, packet losses can be modeled as additional delays; see Seuret et al. (2006).

Quantization and coding
The first problem considered in the literature is related to the minimum information rate which is needed for the stabilization of a linear system. In Nair and Evans (2003, 2000); Tatikonda and Mitter (2004) it has been shown that this minimum rate depends on the unstable eigenvalues of the system. Several generalization of this have been proposed, e.g. Ishii and Başar (2005); Matveev and Savkin (2005); Fagnani and Zampieri (2004). In particular, these results hold true for infinite memory quantizers. In Fagnani and Zampieri (2004) the quantized stabilization through finite memory and by memoryless quantizers is treated. In the scenario in which the digital communication channel is noisy, the techniques proposed above do not work. Some important contributions have been given in Sahai and Mitter (2006) where the fundamental limitations due to noise are explored. Some other important contribution on this directions are given in Simsek et al. (2004); Martins et al. (2006).

QoS and control
If the controller is designed only considering the plant model and the specifications, without considering the problem of the implementation on a distributed system, then it is necessary to evaluate the QoS provided by the distributed computing system in order to characterize the robustness of the controller with respect to the provided QoS. In this way it is possible to compare different control strategies according to their sensitivity to the QoS level; see Juanole and Mouney (2006). Therefore, on the one hand this method requires to identify all the mechanisms

which govern the QoS, to model the QoS and to evaluate it, and, on the other, to evaluate its impact on the process control application. Moreover it is worth to mention methods in which the controller is designed by integrating the behavior of the distributed system. Either the knowledge of the QoS is evaluated off-line through a model of the QoS Georges et al. (2006) or this knowledge is obtained online by measuring the QoS by means of metrology services Lepage et al. (2006). We finally mention the use of control over network methods in a robotic context Fraisse (2006).

3.3 Multiagent systems

In the area of distributed control some important contributions have been done in the last years.

Recently new interesting results have been proposed in the context of distributed optimal control. In D'Andrea and Dullerud (2003) an efficient strategy for the design of distributed controllers have been proposed. More recently Rotkowitz and Lall (2006) derived necessary and sufficient conditions distinguishing when a decentralized optimal control can be recast into a convex optimization problem. While distributed estimation for sensor networks is a quite active area of research in the field of communication theory, computer science and signal processing of the Proceedings of the IEEE (2003); issue of IEEE Trans. on Information Theory (2006), only recently considerable attention has been devoted to this area within the control community. Olfati-Saber and Murray (2004) first related the distributed estimation problem to the problem of finding a consensus in a distributed manner. This idea suggested a new approach to distributed Kalman filtering Spanos et al. (2005); Olfati-Saber (2006b). Murray et al. (2007) provides a nice survey on this subject. In Xiao and Boyd (2004) it is shown how the previous problems can be recast as an convex optimization problem. Interesting extensions to networks with switching topology can be found in the seminal paper Tsitsiklis and Athans (1984) and in Jadbabaie et al. (2003); Ren and Beard (2005); Xiao and Wang (2006), while extensions to randomly switching topology have been proposed in Boyd et al. (2006).

The literature on multi-robot systems is extensive and rapidly growing. References with a robotics focus include the survey in Cao et al. (1997), the text Arkin (1998) on behavior-based robotics, the recent special issue Arai et al. (2002) of the IEEE Transaction on Robotics and Automation, and the survey article Gerkey and Mataric (2004) on task allocation problems. A comprehensive modeling paradigm is also beginning to emerge. An important contribution towards a network model of mobile interacting robots is introduced in Suzuki and Yamashita (1999). This model consists of a group of identical "distributed anonymous mobile robots" characterized as follows: no explicit communication takes place between them, and at each time instant of an "activation schedule," each robot senses the relative position of all other robots and moves according to a pre-specified algorithm. Communication complexity for control and communication algorithms in multi-robot systems are analyzed in Klavins (2003). A comprehensive set of models and the time complexity analysis of numerous algorithms are proposed in Martínez et al. (2008a,b). With regards to distributed motion coordination algorithms, much progress has been made on pattern formation (see Suzuki and Yamashita (1999); Belta and Kumar (2004); Justh and Krishnaprasad (2004); Smith and Bullo (2007); Sepulchre et al. (2007)), flocking (see Jadbabaie et al. (2003); Tanner et al. (2007); Olfati-Saber (2006a)), self-assembly (see Klavins et al. (2006)), swarm aggregation (see Gazi and Passino (2003)), gradient climbing (see Ögren et al. (2004)), deployment (see Cortés et al. (2004); Cortés and Bullo (2005); Ganguli et al. (2006)), rendezvous (see Ando et al. (1999); Lin et al. (2004a,b); Cortés et al. (2006)), cyclic pursuit (see Bruckstein et al. (1991); Marshall et al. (2004)), vehicle routing (see Lumelsky and Harinarayan (1997); Sharma et al. (2005)), and connectivity maintenance problems (see Zavlanos and Pappas (2005); Savla et al. (2006)). Also specific research has been devoted to distributed task allocation problems. Distributed auction algorithms are discussed in Castañón and Wu (2003); Moore and Passino (2007) building on the classic works in Bertsekas and Castañón (1991, 1993). Distributed MILP solver is proposed in Alighanbari and How (2006). A spatially distributed geometric scheme is proposed in Frazzoli and Bullo (2004). Finally, target allocation for vehicles with nonholonomic constraints is studied in Rathinam et al. (2007); Savla et al. (2007).

4. FORECAST

4.1 Control of networks

The area of control of networks is expected to grow since control methodologies are explicitly being applied to new problems. For congestion control, more accurate network models will be considered, e.g., in which each communication channel may have a different time-varying and uncertain time delay. The coupling between wireline and wireless networks is also of growing importance for wireless Internet and other applications; see Hossain et al. (2004); Möller et al. (2004, 2005).

Theories and engineering principles for dynamically allocating resources in wireless ad hoc networks to ensure quality of service are needed for a wide range of applications. One interesting suggestion is to have a formal and possibly optimization-based theory for the design of network protocols based on a model of the underlying network and on a specification of the application requirements. The application of mathematical decomposition techniques to networked systems has just begun to appear; see Chen et al. (2005); Chiang (2005); Johansson and Johansson (2006).

Breaking up the layered structure of the networking stack may also have negative consequences, partially in terms of maintenance and compatibility issues but also in terms of the resulting performance. In particular, it has been observed that cross-layer coordination protocols can introduce dependency relations and unintended interactions; see Kwadia and Kumar (2005). In some situations, adaptation mechanisms in different layers can start working against each other, leading to worse practical performance than in a layered network. It is thus important to develop control theoretic tools for analyzing protocol dynamics in order to guarantee stable and efficient overall behavior.

Finally web-server systems pose another type of control of computer networks problems; see Hellerstein et al. (2004); Robertsson et al. (2003).

4.2 Control over networks

Delays
As mentioned above, much effort aimed at making the network controlled system robust to constant, or predictable delays. This is worth being continued and, if possible, generalized to more general cases. For instance, how to avoid a penalizing buffer strategy? How to predict the delay without a model? Few results make use of delay identification algorithms so to improve the control through adaptive strategies. This could be linked to recent progresses in delay estimation; see Belkoura et al. (2006); Drakunov et al. (2006). The control/protocol co-design probably remains also to be explored more deeply.

Data loss
The previous work was mainly concerned with single sensor-controller-actuator. Current research is concerned with multiple distributed sensors, actuators and controllers. In this scenario many problems still remain to be solved. For example it is not clear whether each sensor should send the raw measurement or a local estimate of the state. In the latter case, it is not trivial how to optimally fuse local state estimates. Moreover, when controllers are distributed and can receive local information, there is a need for coordination in order to achieve a common goal. How this coordination should be performed is still an open problem, even at the level of architecture design.

Quantization and coding
As mentioned above, much work still needs to be done in developing control and estimation strategies which work when the data are transmitted through a digital noisy channel. This is a relevant problem because, when using wireless communication networks, the noise may not be negligible. The most common models of noisy digital channels is the binary symmetric channel and the erasure channel. Although some fundamental results are available in the literature, there has not been enough effort in the development of error correcting codes which are adapted to control and/or estimation goals and which are practical from the algorithmic complexity point of view.

QoS and control
Specific efforts will be needed towards the development of co-design strategies, namely strategies in which the design of the scheduling, of the data transfer protocols and of the controller is dealt jointly. In particular, wireless networks and schemes for dynamic priorities for the message scheduling will be considered. The priorities will be based on the performance of the control application.

4.3 Multiagent systems

Many interesting questions still remain unanswered in the area of multi-agent systems. Indeed, it is widely unclear how to design of local laws which yield a prescribed global behavior. The picture is clearer in some specific and simple cases, such as, for instance, in the distributed averaging problem. But even in this simple example there are still many things to be understood. For instance it is not yet clear what network topologies yield better performance in terms of robustness to failure, flexibility, reliability and adaptivity. The mathematical instruments are still insufficient, though there are promising methodologies which are emerging; see for instance Albert and Barabási (2002). Finally, much work will be necessary in order to connect the system theoretic approach to distributed estimation for sensor networks to the techniques which are being proposed for solutions of the same problems in the fields of communication and information theory, computer science and signal processing.

On the subject of multi-robot networks, future research will focus on developing a broad theoretical modeling framework for robotic networks with a rich application catalog of combinatorial and geometric tasks. For a detailed realistic model combining mobile robotics and ad hoc wireless networking, there will be much interest in designing and analyzing algorithms with appropriate performance, robustness and scalability properties for various task allocation, surveillance, and information gathering applications. It is fair to say that we should aim at developing a full suite of results on time, communication, space and energy complexity for algorithms which tolerate processor and communication failures in face of wireless and physical congestion. From a technical viewpoint, the key challenges lay at the intersection of distributed computation, combinatorial optimization, computational geometry, and control theory.

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