INVITED PAPER

Control and Communication Challenges in Networked Real-Time Systems

Systems now have the ability to do data processing and control at remote locations and can be coordinated through digital, even wireless, networks to meet overall objectives.

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ABSTRACT | A current survey of the emerging field of networked control systems is provided. The aim is to introduce the fundamental issues involved in designing successful networked control systems, to provide a snapshot assessment of the current state of research in the field, to suggest useful future research directions, and to provide a broad perspective on recent fundamental results. Reflecting the goals of the Special Issue itself, this paper surveys relevant work from the areas of systems and control, signal processing, detection and estimation, data fusion, and distributed systems. We discuss appropriate network architectures, topics such as coding for robustly stable control in the presence of time-varying channel capacity, channels with fixed versus adaptively variable data width, issues in data rate problems in nonlinear feedback problems, and problems in routing for stability and performance. In surveying current research on networked control systems, we find that recent theoretical advances and target applications are intimately intertwined. The common goal of papers in the Special Issue which follows is to describe key aspects of this relationship. We also aim to provide a bridge between networked control systems and closely related contemporary work dealing with sensor networks and wireless communication protocols.

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I. INTRODUCTION

In technological terms, networked control systems are comprised of the system to be controlled and of actuators, sensors, and controllers whose operation is coordinated through some form of communication network. From a macroscopic systems biology point of view, however, the components might be identified as neurons, muscles, neural pathways, and the cerebral cortex. The universal feature of networked control systems is that the component elements are spatially distributed, may operate in an asynchronous manner, but have their operation coordinated to achieve some overall objective. The proliferation of these systems has raised fundamentally new questions in communications, information processing, and control dealing with the relationship between operations of the network and the quality of the overall system's operation. A wide range of research has recently been reported dealing with problems related to controlling the formation of *ad hoc* networks of spatially distributed systems, system-dependent data rate requirements in digital feedback channels, real-time fusion and registration of data from distributed heterogeneous sensors, and the theory of cooperative control of networks of autonomous agents. The current state of the art of such research is the subject of this Special Issue of the Proceedings of the IEEE.

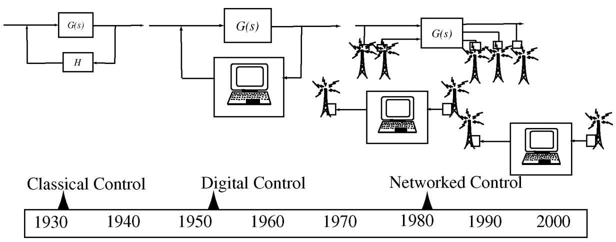

Fig. 1. ***We take 1932 (publication of Nyquist's paper "Regeneration Theory") as the birth date of modern feedback control. Digital control concepts were being widely discussed as early as the 1950s. One of the earliest networked control systems technologies apparently began in 1983 when Bosch GmbH in Stuttgart initiated an internal program to evaluate the concept of using a data network in automobile control applications. In 1986, Bosch introduced the Control Area Network (CAN).***

A. Evolution of Control Technology

Fig. 1 illustrates the timeline of the technological evolution from classical feedback control to digital control to networked control. Although work in the 19th century which followed J. C. Maxwell's [82], [83] 1868 publications on steam engine regulation using centrifugal governors (and even earlier related work of Huygens, [62]) dealt in an increasingly rigorous way with design principles of specific feedback systems, the very general methods of design and analysis that followed Nyquist's 1932 paper [95] were revolutionary insofar as they provided principles that could be applied to virtually any feedback system. Between 1930 and 1950, a solid theoretical foundation for frequency domain methods was laid by the pioneering work of Nyquist, Bode, Nichols, and Evans; see [20]–[23], [25], [27], and [84]–[86]. After 1950, there was growing interest in the use of digital computers as instrumentation for feedback control. In passing from the continuous-time/continuous-state models used in classical feedback designs to the discrete-time/quantized-state design of digital control, design choices involving sampling rates, effects of finite word length, and compensation for phase lags needed to be made. After half a century of research and implementation experience, the foundations of digital control theory are now firmly established and can be found in textbooks such as [9], [48], and [116]. For a general introduction to control and to linear and nonlinear system theory see [5], [49], [51], [69], [104], and [107].

Control systems with spatially distributed components have existed for several decades. Examples include chemical processes, refineries, power plants, and airplanes. In the past, in such systems the components were connected via hardwired connections and the systems were designed to bring all the information from the sensors to a central location where the conditions were being monitored and decisions were taken on how to act. The control policies then were implemented via the actuators, which could be valves, motors, etc.

What is different today is that technology can put low-cost processing power at remote locations via microprocessors and that information can be transmitted reliably via shared digital networks or even wireless connections. These technology-driven changes are fueled by the high costs of wiring and the difficulty in introducing additional components into the systems as the needs change.

In 1983, Bosch GmbH began a feasibility study of using networked devices to control different functions in passenger cars. This appears to be one of the earliest efforts along the lines of modern networked control. The study bore fruit, and in February 1986 the innovative communications protocol of the Control Area Network (CAN) was announced at the Congress of the Society of Automotive Engineers, Detroit, MI. By mid 1987, CAN hardware in the form of Intel's 82526 chip had been introduced, and today virtually all cars manufactured in Europe include embedded systems integrated through CAN. Networked control systems are found in abundance in many technologies, and as is discussed in detail in the paper [S1] which follows, all levels of industrial systems are now being integrated through various types of data networks.

Although networked control system technologies are now fairly mature in a variety of industrial applications, the recent trend toward integrating devices through wireless rather than wired communication channels has highlighted important potential application advantages as well as several challenging problems for current research. These challenges involve the optimization of performance in the face of constraints on communication bandwidth, congestion, and contention for communication resources, delay, jitter, noise, fading, and the management of signal transmission power. These are among the issues to be addressed in the papers that follow in this Special Issue.

While the greatest commercial impact of networked control systems to date has undoubtedly been in industrial implementations, recent research suggests great potential together with significant technical challenges in new applications to distributed sensing, reconnaissance and other military operations, and a variety of coordinated activities of groups of mobile robot agents. Taking a broad view of networked control systems, we find that in addition to the challenges of meeting real-time demands in controlling data flow through various feedback paths in the network, there are complexities associated with mobility and the constantly changing relative positions of agents in the network.

B. Changes in Control Systems Research Directions

The changes in the scope and implementation of control systems fueled primarily by technological factors, low-cost processing, and integrated communications have caused two main changes in the theoretical approaches to control system analysis and design. The first has to do with the explicit consideration of the interconnections; the network now must be considered explicitly as it affects the dynamic behavior of the control system. The second change has to do with a renewed emphasis on distributed control systems.

Regarding the first change, control systems are redefined in the sense that there is an additional component to the plant, controller, sensor, and actuator components, namely the network that represents the interconnections among components. The network has become a factor because of the use of digital communication networks shared by other applications. There, media access by the sensor that needs to transmit data may not be immediate and communication delays and packet losses may occur. Furthermore, the increasing use of wireless communications introduces new issues such as fading and time-varying throughput in communication channels. As a result of these changes, the effect of the interconnections needs to be explicitly addressed in networked control systems.

The second area of change is the shift of emphasis from centralized to distributed control systems. The fact that there is ample processing power available at low cost that can be embedded almost anywhere opens a vast array of new possibilities. Sensor data can be processed locally and control policies can be implemented again locally, without needing a central decision maker. The remote units act locally but they must coordinate their actions to serve global goals. In this way, there is no need for large amounts of data being exchanged over the network. The common wisdom is that distributed control can never be as good and effective as centralized control. Is this assumption correct? Intuitively it is true, assuming that there are no delays when data are sent to and from the central processing unit. When delays are present (and this is unavoidable under current technology trends of shared digital networks and wireless connections), distributed control has the potential of being superior to centralized control, since sharing local information and acting upon it may be relatively delay free. The distributed control systems can then be seen as consisting of clusters of sensors, actuators, processing units, and communication devices that are rather loosely interconnected, sharing perhaps only supervisory information. An example of a distributed control system is a group of unmanned air vehicles (UAVs) that coordinate their flight directions and velocities to fly in formation.

Because of these changes in the approaches to controlling systems, several new concerns need to be addressed. Several areas such as communication protocols for scheduling and routing have become important in control when considering, for example, stability, performance, and reliability. Algorithms and software that are capable of dealing with hard and soft time constraints are very important in control implementation and design, and thus areas such as real-time systems from computer science are becoming increasingly important. There is also some reordering of control concepts due to changes in importance to control applications. Control concepts that were of interest before have been brought to the forefront and assumed new importance because of the changing circumstances. An example is actuator saturation or constraints, which plays an even more important role today, since networked systems are expected to run intermittently open loop. The fact that there are actuator constraints implies that unstable systems are much more restricted from running open loop for extended periods of time as it may not be possible to reverse direction in an unstable trajectory if the system has departed significantly from an equilibrium point.

At a more fundamental level, control theorists have been led to re-examine the open (feed-forward) versus closed-loop (feedback) control issues. The desire to do better than holding the control input value constant during open loop intervals, as is typically the case when using standard zero-order hold devices, has led to the introduction of increased explicit knowledge about the plant in the controller and to model based control architectures in certain studies; see [88]. There has also been renewed emphasis on increased autonomy that allows the system to run without feedback information for extended periods of time. This has brought forth the area of autonomous intelligent control and consideration of approaches and methodologies on how to build such systems; see [6].

Distributed control is related to the areas of decentralized control and of large-scale systems, which were studied extensively in the 1970s. In the case of large-scale systems several results were derived, primarily on the stability of such systems. Typically, it would be assumed that the interconnections had certain strength, and then some form of Lyapunov theory would be applied. Other results were also derived. (See the survey on large scale systems [103].)

About 30 years ago, decentralized control was studied, where the controller had special structure; for example, the controller could be a diagonal matrix, so that measurements from the first output were used to decide only the first control input. These (block) diagonal special structures introduced restrictions conveniently expressed by the notion of fixed modes [119]. Note, however, that the plant in decentralized control was still a single tightly connected unit and not a rather loosely interconnected group of complete systems, which is the typical case in distributed control.

In addition to the fixed mode results already mentioned, there is also on-going work on decentralized supervisory control of discrete-event systems using finite automata or Petri Net models; see [63] and [102].

The whole area of sensor networks is very relevant, although the networks we are interested in are sensor and actuator networks. In networked control systems data are not only gathered and processed as in sensor networks but are used in decision algorithms to derive control policies implemented via the actuators. There are many similarities and also differences [50], [126].

It should be noted that there are several research areas in other disciplines that deal with topics relevant to networked control systems. Optimization is one such area. Of particular interest are distributed optimization algorithms. The area of complex systems studied by physicists using statistical methods is relevant as well. They are interested in modeling systems ranging from the internet to protein metabolic networks in biological organisms. Tools used are graph theory and power distribution laws, and scale-free networks together with phenomena such as the small-world phenomenon are observed.

C. Networked Control Systems Research

Networked control systems research lies primarily at the intersection of three research areas: control systems, communication networks and information theory, and computer science. Networked control systems research can greatly benefit from theoretical developments in information theory and computer science. The main difficulties in merging results from these different fields of study have been the differences in emphasis in research so far. In information theory, delays in the transmitted information are not of central concern, as it is more important to transmit the message accurately even though this may involve sometimes significant delays in transmission. In contrast, in control systems delays are of primary concern. Delays are much more important than the accuracy of the transmitted information due to the fact that feedback control systems are quite robust to such inaccuracies. Similarly, in traditional computer science research time has not been a central issue since typical computer systems were interacting with other computer systems or a human operator and not directly with the physical world. Only recently, areas such as real-time systems have started addressing the issues of hard time constraints where the computer system must react within specific time bounds, which is essential for embedded processing systems that deal directly with the physical world; see [70], [105], and [106].

The work described in this special issue is summarized at the end of this paper; see also earlier special issues and additional references in [7], [8], and [57]. Where do we go from here? So far, researchers have focused primarily on a single loop and stability. Some fundamental results have been derived that involve the minimum average bit rate necessary to stabilize a linear, time-invariant system. Although progress has been made, much work remains to be done. In the case of a digital network where information is typically sent in packets, the minimum average rate is not the only guide to control design. A transmitted packet typically contains a payload of tens of bytes, and so blocks of control data are typically grouped together. This enters into the broader set of research questions on the comparative value of sending 1 bit per second or 1000 bits every 1000 seconds—for the same average data rate. In view of the typical actuator constraints, an unstable system may not be able to recover after 1000 seconds.

An alternative measure is to see how infrequent feedback information is needed to guarantee that the system remains stable. See, for example, [88] and [89], where this scheme has been combined with model-based ideas for significant increases in the periods where the system is operating in an open-loop fashion. Intermittent feedback is another way to avoid taxing the networks for sensor information. In this case, every so often the loop is closed for a certain-fixed or time-varying period of time [41]. This may correspond to opportunistic, bursty situations where the sensor sends up bursts of information when the network is available. The original idea of intermittent feedback was motivated by human motor control considerations.

There are strong connections with cooperative control. There, researchers have used spatial invariance ideas to describe results on stability and performance [100]. If spatial invariance is not present, then one may use the mathematical machinery of graph theory to describe the interaction of systems/units and to develop detailed models of groups of agents flying in formation, foraging, cooperation in search of targets or food, etc. An additional dimension in the wireless case is to consider channels that vary with time, fade, or disappear and reappear. The problem, of course, in this case becomes significantly more challenging. There is ongoing fundamental work in this area reported in this special issue; see [S5]–[S7]. Consensus approaches have also been used which typically assume rather simple dynamics for the agents and focus on the topology considering fixed or time-varying links in synchronous or asynchronous settings; see [26], [45], [46], [65], and [114].

Implementation issues in both hardware and software are at the center of successful deployment of networked control systems. Data integrity and security are also very important and may lead to special considerations in control system design even at early stages.

What then are areas that have been or are being studied and what are research areas where important challenges remain?

Overall, single loop and stability have been emphasized and studied under quantization of the sensor measurements and actuator levels. Research is needed to understand multiple interconnected systems over realistic channels that work together in a distributed fashion towards common goals. Performance is key in making such systems attractive to practitioners; see, for instance, [S5] in this issue of the Proceedings. Note that limits to performance in networked control systems appear to be caused primarily by delays and dropped packets. Other issues being addressed by current research are actuator constraints, reliability, fault detection and isolation, graceful degradation under failure, reconfigurable control, and ways to build increased degrees of autonomy into networked control systems. Some of this work will provide the content for future special issues.

D. Present Special Issue

The papers in this Special Issue have been selected to reflect a number of important areas of current research on networked control systems. Broadly speaking, these are: 1) the assurance of control performance in the face of communication constraints between network nodes; 2) the effects of latency, network overhead, noise, delay, and packet dropouts; 3) consensus, coverage, and optimized cooperation in systems of multiple mobile agents; and 4) information patterns for decentralized control of networks of mobile agents. The growing interest in networked control systems has stimulated new research in a variety of related areas including communications theory and systems biology. Specifically, real-time requirements suggest new approaches to the design of network protocols as solutions to optimization problems. There is an emerging two-way cross fertilization involving systems biology and networks in which the language of data networks has been used in modeling biological sensing processes, while at the same time biology has inspired new approaches to multisensor fusion and real-time perception.

When the two guest editors (Antsaklis and Baillieul) edited a similar special issue of the IEEE Transactions on Automatic Control in 2004 [7], they ended some introductory remarks by apologizing that it had been possible to only cover a portion of the very active area of networked control systems. The situation now is no better. The coverage in the current Special Issue is broader, but the area has also been expanding very rapidly. Since it is simply not possible to provide a comprehensive treatment of all topics that have been addressed, certain research topics have not received equal attention. For example, important work dealing with the relationships between communication channel capacity and frequency domain representations of linear feedback systems is not emphasized in the papers appearing in this issue. The reader is referred to the recent research literature—especially papers Elia [39] and Tatikonda *et al.* [113] in our previous special issue on networked control systems or to the recent work of Martins [81].

The remainder of the paper will serve to introduce the research contained in this Special Issue and to place this into the broader context of current research in the field. Section II provides a historical introduction. Section III discusses robustness and risk-sensitive control for networked control systems. Section IV treats spatio-temporal patterns of information flow. Section V provides a summary description of the content of the papers and their relationships with each other and with the larger field.

II. EARLY FOUNDATIONS OF NETWORKED CONTROL

Research on digital control began appearing in the literature in the 1950s soon after the introduction of digital computers. Indeed, the first paper published in Volume 1, Number 1 of the *IRE Transactions on Automatic Control* (predecessor of the current IEEE Transactions on Automatic Control) described the implementation of a feedback control for a second-order plant using a four-bit switching logic. The main results of the paper involved strip chart readings from their instruments, and in the parameter range they chose to study, this early approach to quantized feedback control employed a simple switching logic which was remarkably effective. Despite this and other early interest by control visionaries (e.g., Kalman [68]), digital control did not become major focus of research until the introduction of inexpensive and reliable microprocessors in the 1970s. (See G. Zames [123] for a charming personal perspective on developments of the time.) Similarly, although control networks were introduced in the 1980s, it has only been within the last decade, with wireless cellular communications and several other enabling technologies attaining maturity, that the research community has focused significant attention on the theoretical foundations of networked control systems. Despite the recent surge in interest, it is worth noting that there is an intellectual backdrop in the control literature predating the Bosch Company's 1986 introduction of the CANbus. A great deal of current research on networked control systems features a cross disciplinary blending of ideas from control, communications, and information theory, but there is a much older body of literature describing some of the basic elements of the enabling theory of information-based control. Between the 1960s and 1990, a great deal of research in control appeared aimed at making connections with Shannon's visionary theory of information. Zames' work on Kolmogorov entropy [124] and Akaike's information criterion and related shortest description criteria in identification theory [1] are pertinent references.

We also wish to mention the network theory developed in the 1950s and 1960s from a circuit point of view that made possible the analysis and design of systems ranging from electric power transmission lines to very large-scale integration (VLSI) circuits via concepts such as Thevenin's and Norton's theorems, wave variables, scattering theory, and passivity; see [72]. Some of these concepts have been very useful in digital filter design (wave filters) and may be as useful in the design of networked control systems that consist of many interconnected components.

Driven by technological developments associated with the rise of digital electronics, models of dynamical systems in which both time and state variables are quantized became an essential part of the control theory of the 1970s and 1980s. Early work in which the qualitative dynamics of quantized systems was related to the information content of feedback signals appeared in a group of papers by D. Delchamps in the early 1990s [32]–[36]. Based in part on earlier work on digital feedback [10], this work showed that if the feedback measurements in a control system are quantized (as they would be in a typical digital control implementation), and if the system is open-loop unstable, then there is a minimum rate at which feedback information must be processed and used to close the control loop if the system is to be stabilized. Moreover, it was observed [34] that near this minimum data rate, the closed-loop system will exhibit chaotic dynamics.

Following Delchamps, an important independent line of research that focused on the interplay among coding, estimation, and control was initiated in the early 1990s by W. S. Wong and R. W. Brockett [121], [122]. A preliminary version of some of this work appeared in [120], and a preprint version of [122] was also circulated in 1995. This research was concerned with the role coding of feedback signals played in determining the stability of a linear system with communication constrained feedback channels. A connection was established between stabilizability and an inequality relating the feedback channel data rate to the eigenvalues of the open-loop system. Both a necessary condition and a sufficient condition were given, with the two coinciding for scalar linear systems.

Similar sets of research issues emerged around the same time in hybrid and switched systems, where the study of dynamical systems was focused on models that contained both continuous time-driven dynamics and discrete event-driven dynamics. Issues such as stability of systems controlled by switching strategies were studied; see [2]–[4].

Research on the design of control laws for communication-constrained feedback channels was also reported around the same time. In [28], Borkar and Mitter considered the LQG problem for coded feedback and communications constraints. Related work on recursive state estimation using data passed through rate-limited channels has been reported by a number of researchers including Dokuchaev and Savkin [37], Li and Wong [77], Liu and Wong [78], and, as mentioned previously, Wong and Brockett [121].

A high-water mark in the study of quantized feedback using data-rate limited feedback channels is known as the *data-rate theorem*. This states that *for any linear time-invariant plant having open-loop poles $a_1, \ldots, a_k$ in the right half-plane, a quantized feedback law can be designed to produce a bounded response if and only if the data-rate R around the closed feedback loop satisfies the* data-rate inequality

$$R > \log_2 e \sum \Re(a_i). \tag{1}$$

That is, the larger the magnitude of the unstable poles, the larger the required data rate through the feedback loop. This intuitively appealing result was proved independently under a variety of assumptions (see [11], [13], [29], [93], [94], [109], [110], [112], and [122]), indicating that it quantifies a fundamental relationship between unstable physical systems and the rate at which information must be processed in order to stably control them. It is also remarkable that the theorem involves only the rate at which information can be processed and communicated through the feedback loop. There are no *a priori* restrictions on how this information is encoded, and for scalar systems, it is known that a bounded response may be produced by a very coarse (e.g., single bit) set of control values, transmitted rapidly, or a finer set of control values (say 2^n distinct values), each of which is transmitted less frequently ($1/n$th as often).

These results establish some essential requirements for stability. It is important to also address this problem in settings where there are control input constraints, packet transmission losses, and a tendency for bursty opportunistic communications under severe media access and bandwidth restrictions.

When performance requirements require more than merely a bounded response, source coding of control signals must be tailored to achieve the desired performance, as will be seen in Section III.

III. COMMUNICATION-CONSTRAINED PERFORMANCE

Current research on networked control systems is proceeding rapidly and in many directions. Within the scope of this Special Issue, several important emerging topics have not been emphasized. These include new results on robustness and risk that are of special importance in the context of communication-constrained control. Paper [S5] discusses recent research on design tradeoffs between complexity of the encoding of control signals and the performance goals that can be achieved by the closed-loop system. One performance goal which has received increasing attention in the recent literature is robustness with respect to time variability of the channel capacity of the feedback loops. Another topic of emerging importance involves *risk* and *failure* of networked control systems. In most wireless network technologies, failure involves loss of connectivity to the network, e.g., dropped cell phone calls, loss of Internet connection, etc. Failure modes in networked control systems are qualitatively different and the risk and cost of failure must be taken into account. If an open-loop unstable plant fails to receive more than a certain critical number of packets from a controller, it will become unrecoverably unstable. In this section, we briefly discuss the emerging theory of risk and failure associated with noise and communications errors in networked control systems.

A. Coding for Robustness to Time-Varying Data Rates

Current research on feedback coding for control over feedback channels with communications constraints typically involves quantized control. To fix ideas, we consider an n-dimensional system with scalar input

$$\dot{x} = Ax + bu. \quad (2)$$

Quantized control involves a discrete set $\mathcal{U} \in \mathbb{R}$ of control values and a *quantizer* or *selection function* $f : \mathbb{R}^n \to \mathcal{U}$ which associates an element of $\mathcal{U}$ to each point in the state space. Control quantization may involve either a finite or infinite set of control levels. Examples of the former arise in modeling feedback control with an n-bit A/D converter in the loop. Examples of the latter include the so-called logarithmic quantizers studied by Elia and Mitter [38]. Another important distinction is between quantizers which are static and those which are time varying. Static quantizers can achieve asymptotic stability only if they are infinite and have increasingly higher precision near the origin. With time-varying quantizers, it is possible to achieve asymptotic stability even in the case that the control set $\mathcal{U}$ contains only two values. (See Li and Baillieul [73] for details.) For quantization which is static and is such that the number of control values $|\mathcal{U}|$ is finite, it is only possible to achieve a certain *practical stability*, where the system operation is ultimately confined to a bounded set. This section will briefly consider feedback designs which involve static quantization with a finite set $\mathcal{U}$ of control values.

When communication channels in a data network are shared resources among multiple user nodes, network congestion and contention for bandwidth pose challenges for control implementations in which there are hard real-time requirements. In order to implement stable controllers, certain baseline necessary conditions must be satisfied, for instance, the conditions of the data-rate theorem in the case of a finite-dimensional linear system. There are additional considerations, however, in designing control systems which make maximally effective use of a shared channel network. It is well known that when the feedback channel capacity is near the data-rate limit, control designs will typically exhibit chaotic instabilities; see [12], [34], and [43]. While degraded performance cannot be avoided at low data rates, a good feedback coding should allow for improved performance, approaching the continuous time, continuous state idealization when data rates are high. We briefly describe some of the properties of control designs which perform well at high data rates while degrading gracefully as data-rate constraints become severe.

Consider the n-dimensional system (2). We shall assume that feedback control will be encoded using a finite $2N$ or $2N+1$ letter alphabet of control values $\mathcal{U} = \{u_{-N}, u_{-(N-1)}, \ldots, u_{(N-1)}, u_N\} \in \mathbb{R}$. We also assume there is a *selection function* $f : \mathbb{R}^n \to \mathcal{U}$ which associates an element of $\mathcal{U}$ to each point in the state space $\mathbb{R}^n$. It is convenient to assume that the set is symmetric with respect to the origin: $u_k \in \mathcal{U} \Longrightarrow -u_k \in \mathcal{U}$, and we explicitly account for this in the notation $u_{-k} = -u_k$. We also assume that $f(-x) = -f(x)$. The inverse images $\mathcal{R}_i = f^{-1}(u_i)$, $u_i \in \mathcal{U}$ are called *control regions*. We shall be interested in *sample-and-hold* types of control, whose evolution is given by

$$x(t_j + \tau) = e^{A\tau}x(t_j) + \int_0^\tau e^{A(\tau-\sigma)} bf\big(x(t_j)\big)d\sigma, \quad \text{for } 0 \le \tau < t_{j+1} - t_j \quad (3)$$

where the sequence $t_0 < t_1 < t_2 < \cdots$ lists the time instants at which the state is sampled and control actuation is (instantaneously) applied. (See [73] and [75] for information about the case where there are delays—possibly time-varying—between sampling and actuation.)

Assume that the system is such that for all sampling sequences $t_0 < t_1 < \cdots$ with $t_{j+1} - t_j$ less than some prescribed critical value, Θ_0, there is a compact set $K \subset \mathbb{R}^n$ which contains the origin and is invariant under the state transition (3). Systems with finite control alphabets for which it is possible to find such invariant sets include those whose open-loop poles (eigenvalues of A) are real and distinct. We refer to [73]–[75] for more information.

Given Θ_0 and the corresponding compact invariant set $K \subset \mathbb{R}^n$ mentioned previously, we say a control design associated with a selection function f is *regular* if for any neighborhood $\mathcal{N}$ of the origin, there exists a value $h \le \Theta_0$ such that for all sampling sequences satisfying $\sup_{j\ge 0}(t_{j+1} - t_j) < h$ and any initial conditions $x(t_0) \in K$, $x(t) \in \mathcal{N}$ for $t \to \infty$.

The neighborhood $\mathcal{N}$ in the definition may be chosen to be arbitrarily small, so that regular control designs provide good quantized approximations of asymptotically stable feedback laws at high data rates. It is clear that feedback codings which provide good performance over a wide range of sampling rates must be regular. Such codings are thus of particular interest in applications where noise or network congestion results in time-varying feedback channel capacity. At present, practical characteristics and design rules for regular coding are the focus of a great deal of research activity. Since this is not yet a mature area, it has not been accorded an entire paper in the Special Issue. Nevertheless, a brief discussion of the qualitative features of regular codings points to some of the general issues that drive current research on source coding of feedback control signals.

The theory of quantized control of scalar systems is fairly well developed [73], but many general issues arise only in higher dimensions. First, we note that in the case of a scalar plant, if we restrict attention to memoryless control laws with no delay between sampling and actuation, then the data rate bound (1) can be achieved regardless of the control alphabet size N. In higher dimensions, matters are not so clear cut. The constructive arguments used in the literature to prove that the data-rate inequality is a sufficient condition for practical stabilizability typically involve complex coding schemes; see, e.g., [93]–[95], [111], and [112]. In [74], it is argued that in the case that the matrix A has a nontrivial Jordan canonical form or has complex eigenvalues, it may be necessary to let the number of control levels increase without bound in order to achieve practical stability as the data-rate approaches the theoretically minimum possible value. We refer to [74] and [75] for details.

In addition to these considerations, performance requirements of the closed-loop system will also influence the preferred size of the control alphabet. To focus the discussion, we shall restrict our attention to systems in which the eigenvalues of A are distinct and real. (Feedback coding for systems with nontrivial Jordan blocks is somewhat more complicated—as explained in [74].) It will also be assumed that all eigenvalues are positive since if this were not the case, we could restrict our discussion to the unstable subspace. We assume that (2) is controllable, and under this assumption, it can be shown that after a suitable change of basis, $A = \mathrm{diag}\{a_1, \ldots, a_n\}$, $b = (a_1, \ldots, a_n)^T$, and $a_n > a_{n-1} > \cdots > a_1 > 0$.

In [75], we have presented a feedback control coding which decouples the modes in a single-input linear system, so that effectively there are n parallel scalar systems whose evolution using a sample and hold feedback law is given by

$$x_i(t_{j+1}) = e^{a_i h_j} x_i(t_j) + (e^{a_i h_j} - 1)u(t_j) \tag{4}$$

where $t_0 < t_1 < t_2 < \ldots$ are the sampling instants and $h_j = t_{j+1} - t_j$. A single-bit (binary) control law for this subsystem takes a particularly simple and intuitive form

$$u(x) = \begin{cases} -1, & \text{if } x \geq 0 \\ 1, & \text{if } x < 0. \end{cases} \tag{5}$$

Suppose that there is a uniform upper bound Θ: $0 < h_j < \Theta$ for $j = 1, 2, \ldots$. Then, the control (5) makes the interval $-1 \leq x_i \leq 1$ invariant and the interval $[-(e^{\Theta} - 1), e^{\Theta} - 1]$ both invariant and attracting, provided that $\Theta < (\log_e 2)/a_i$. If it is possible to let this bound on the sampling intervals become arbitrarily small, the motion of (4) can be confined to an arbitrarily small interval around the origin. In the limit, this quantized system thus becomes asymptotically stable. We refer the reader to [75] for information on feedback coding for decoupling.

Another approach to feedback coding involves what we shall call *parallel hyperplane quantization*. These designs provide quantized approximations to standard constant-gain feedback laws for linear systems. For high data-rate channels, the designs have the desirable property that they are available from classical theory and design methodologies and can be guaranteed to provide desired levels of performance in terms of such classical design criteria as control energy, loop-shaping, and so forth. For constrained data-rate channels, however, they may be less desirable than designs which give more weight to optimized patterns of information flow which may, for instance, differentially assign bandwidth to different modes. (See [75] for more information about such designs.) Let $g : \mathbb{R} \to \mathcal{U}$, where $\mathcal{U} \subset \mathbb{R}$ is a finite set of control values as given previously. Assume g is nondecreasing and continuous from the left. Let $k \in \mathbb{R}^n$, $k \neq 0$. A *parallel hyperplane selection function* is a function $f : \mathbb{R}^n \to \mathcal{U}$ that has the form $f(x) = g(k \cdot x)$ for such a g and k. This circle of ideas is well illustrated by two-dimensional (2-D) systems with distinct open-loop poles in the right half-plane as discussed earlier. In terms of the normal form $A = \mathrm{diag}(a_1, a_2)$, $b = (a_1, a_2)^T$ and the continuing assumption that $a_2 > a_1 > 0$, it follows from the classical theory of control design that a constant-gain feedback law $u = -k_1 x_1 - k_2 x_2$ which places the closed-loop poles in the left half-plane will be such that $k_1 < 0$ and $k_2 > 0$. For feedback laws of this form, it is not difficult to show that all stabilizing feedback laws which stabilize the continuous-time system (2) are contained in the set

$$\left\{u(x_1, x_2) = -k_1 x_1 - k_2 x_2 : k_1 < 0, k_2 > 0 \quad \text{and } \frac{a_1}{a_2} < -\frac{k_1}{k_2} < \frac{a_2}{a_1}\right\}.$$

The simplest type of control encoding for such a constant gain control design is the "binary" feedback law

$$u(x) = \begin{cases} -1, & \text{if } k \cdot x \geq 0 \\ 1, & \text{if } k \cdot x < 0. \end{cases} \tag{6}$$

The *selection function* associated with this law is illustrated in Fig. 2. It is an interesting feature that when the state is in either of the two quadrants where $x_1 x_2 < 0$, the faster mode associated with a_2 is accorded preferential treatment. That is to say, the value of the control is chosen as $-\mathrm{sgn} x_2$ [in accordance with (5)] and with no dependence at all on the slow state x_1. Thus, the designated value of the control in $x_1 x_2 < 0$ always forces the state component x_1 in the destabilizing direction. It is intuitively appealing that the less stable state should predominate in determining the value of the control in cases where the goal of stabilizing the slow state is in direct conflict with the goal of stabilizing the fast state. In the two quadrants $x_1 x_2 > 0$, the value of the control prescribed by (6) tends to stabilize both states provided that in the first quadrant the state is above the *switching line* $k_1 x_1 + k_2 x_2 = 0$ or in the third quadrant it is below this line. The switching rule as defined by (6) in the wedge-shaped regions between the x axis and the switching line is counterintuitive in that both state components are moved in destabilizing directions. The

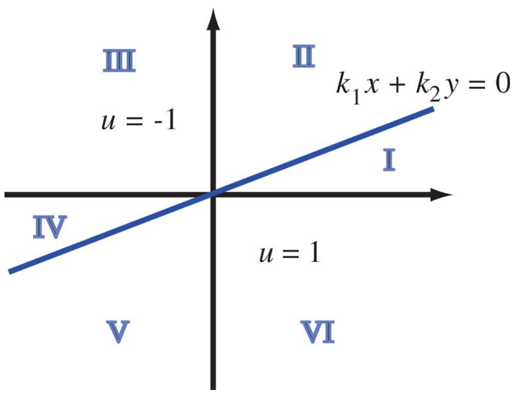

Fig. 2. ***Binary (one-bit) quantized implementation of constant gain feedback control. The are two control regions, the half-planes above and below the switching line. It is useful to subdivide each of these into three subregions which are described in the text.***

switching logic of this binary implementation of constant gain control defines the switching function

$$f(\mathrm{I}) = f(\mathrm{V}) = f(\mathrm{VI}) = 1$$
$$f(\mathrm{IV}) = f(\mathrm{III}) = f(\mathrm{IV}) = -1.$$

Not only are the values of f on regions I and IV counterintuitive, but if the gains are chosen to increase the slope of the switching line (e.g., if poles are placed farther into the left half-plane), the set of states moved in the destabilizing direction increases in size.

At this point, it is useful to distinguish between two cases: $|k_1|/k_2 > 1$ and $|k_1|/k_2 < 1$. In the latter of these two cases, if the feedback is stabilizing, the closed-loop poles are close to the imaginary axis. The closed-loop time constants are slow. A somewhat surprising result is that binary realization of the feedback laws with $|k_1|/k_2 < 1$ fails to achieve practical stability; there are essentially no bounded motions under the binary law (6). This is in contrast to stabilizing designs with $|k_1|/k_2 > 1$ in which case there is always a domain with open interior which is invariant under the transition law (4) with the binary control (6). For a more detailed treatment, we refer to [18].

Before leaving this section, it is worth noting that even using a larger set of control levels, a quantized realization of the case $|k_1|/k_2 < 1$ will fail to be regular. Continuing our consideration of parallel hyperplane quantization for the 2-D normal form, we note that the state evolution law may be thought of as the concatenation of flows

$$\varphi_u(t; x_1, x_2) = \begin{pmatrix} e^{a_1 t}x_1 + (e^{a_1 t} - 1)u \\ e^{a_2 t}x_2 + (e^{a_2 t} - 1)u \end{pmatrix}$$

parameterized by the controls $u \in \mathcal{U}$. In the case $a_2 > a_1 > 0$, each of these flows is associated with a *source* centered at $(-u, -u)$ (in the language of dynamical systems theory). The state transition law (4) prescribes that for a given input u, associated with a region between two switching lines $k_1x_1 + k_2x_2 = s_j$ and s_{j+1} where the s_is are discontinuity points of $g(\cdot)$, the flow is followed until a switching line is crossed. After the switching line is crossed, a new control value is prescribed at the next sampling instant, and the flow associated with that control is followed until yet another switching line is crossed. The case of four control level (2-bit A/D) is depicted in Fig. 3, where the control set is $\mathcal{U} = \{-1, -0.3, 0.3, 1\}$ with switching lines $k_1x_1 + k_2x_2 = -0.8, 0,$ and 0.8. The two flows $\varphi_{\pm r}$ where $r = 0.3$ are depicted in red, while the flows $\varphi_{\pm 1}$ are drawn in green. A detailed analysis of switching among the control flows which is prescribed by the feedback law shows that for small intersampling intervals $h > 0$, there is an attracting limit cycle (depicted by the black curve). The geometry of this limit cycle has only minute dependence on h as $h \to 0$ so that the limit cycle persists as the sampling rate is increased. This limit cycle is large relative to the largest bounded invariant set, and it is precisely because of the persistence of the large amplitude limit cycle as $h \to 0$ that the quantization fails to be regular.

As values of the gain ratio are varied in the range $|k_1|/k_2 < 1$, detailed simulation experiments show that limit cycles persist even in the case that the control set $\mathcal{U}$ has more than four elements. This observation suggests that

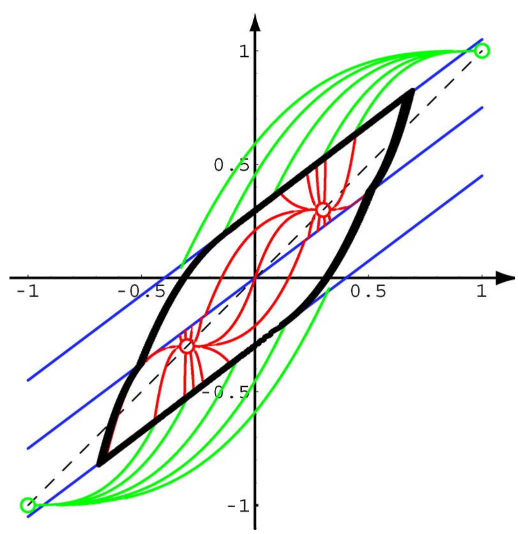

Fig. 3. ***Two-bit (four-level) quantized implementation of constant gain feedback control in the case $|k_1|/k_2 < 1$. Specifically, $k_1 = -2$, $k_2 = 8/3$, $r = 0.3$, and $s = 0.8$. Design is not regular and this results in existence of limit cycle (black curve) which is both large, relative to the operating region, and persistent, as length of sampling interval h tends to zero.***

even standard implementations, using, say, 8- or 12-bit A/D hardware can be expected to perform badly if a closed-loop system response outside a certain prescribed range is called for. The existence of complex dynamics and chaotic instabilities in digital circuits is well documented; see [86]. At present, the role of coding in eliciting or suppressing such instabilities in embedded and networked control systems is not well understood. It remains a fertile area for continuing research. For more information on quantization for feedback signals designed to achieve closed-loop performance objectives beyond mere practical stability, we refer to [S5] and [44]. For a discussion more specifically concerned with *regular* feedback designs, we note that a complete characterization is available in the scalar case, for which we refer to [S5] and [73].

B. Noise, Bit Errors, and the Risk of Instability

For a control system of the form (2), with quantized feedback control values being communicated from a controller to the plant over a noisy feedback channel, randomly occurring bit errors will degrade the system's performance. The extent of this degradation will depend on a number of factors, including how noisy the channel is and whether control levels have been coded in a way that no single bit error in the specification of a control value will cause the plant to use a value which is significantly different from the one specified. If the channel is noisy and bit errors are frequent, performance of the closed loop system may degrade to the point of instability. The likelihood and expected frequency of such severe performance degradation may be most easily understood in terms of a scalar system with a binary encoding of a stabilizing feedback. Consider a continuous-time scalar system

$$g(s) = \frac{1}{s-a} \tag{7}$$

where $a > 0$. A feedback law is implemented over a digital communication channel with the following ideal features.

1) The analog system is sampled at a uniform rate—one sample being taken every h units of time (seconds).
2) One of only two possible values of the control is applied throughout the sampling interval (say $u = \pm 1$).

This system is thus associated with a state transition mapping

$$x(k+1) = \alpha x(k) - \operatorname{sgn}[x(k)](\alpha - 1) \tag{8}$$

where $\alpha = e^{ah}$. It is easy to see that provided that $\alpha < 2$, the interval $[-1,1]$ will be invariant, and this will contain a smaller subinterval $[-(\alpha-1), \alpha-1]$ which is both invariant and attracting. Points $x(k)$ lying outside the larger interval $[-1,1]$ give rise to unbounded trajectories and, consequently, the possibility that a stably operating feedback system can become unstable due to packet losses or bit errors. Single-bit feedback encoding of this type has been shown to provide robust performance when using communication-constrained feedback channels which are subject to variations in channel capacity; see [73] and [75]. It also provides a simple analytical framework for discussing system performance in the presence of noise, bit errors, and packet losses. Using our simple model, it is easy to see that a single bit error can always be tolerated by a system operating in the steady-state invariant interval $[-(\alpha-1),\ \alpha-1]$, provided $\alpha < \sqrt{2}$. More generally, a sequence of $n-1$ successive bit errors can be tolerated by a system which is operating in the invariant interval if and only if $\alpha < 2^{1/n}$. If $2^{1/n} < \alpha < 2^{1/n-1}$, a sequence of $n-1$ successive bit errors will place the system at risk (meaning that some states in the steady state subinterval $[-(\alpha-1),\ \alpha-1]$ will be unstable), and if $\alpha \geq 2^{1/n-1}$, a sequence of $n-1$ successive bit errors will always lead to instability.

We can consider these observations in the context of a serial feedback channel in which bit errors occur randomly in any transmitted sequence of bits in accordance with, say, a binomial probability law having probability p of a bit error occurring in any particular position in the transmitted sequence. Several observations are in order.

First, *for any value of* α, $1 < \alpha < 2$, *after a sufficiently long time, the system* (8) *will, with probability 1, be destabilized by a sequence of bit errors*. A proof may be constructed along the following lines. System (8) operating in the presence of errors may be represented as $x(k+1) = \alpha x(k) - e(k)\operatorname{sgn}[x(k)](\alpha-1)$, where $e(k)$ is a random sequence whose elements are i.i.d. and the values ± 1 with probabilities p and $1-p$, respectively. According to our remarks, there is an integer n such that any sequence of n successive bit errors will destabilize the system. For a sufficiently long sequence $e(1), e(2), \ldots$, the probability of encountering a string of n successive 1s is high, and as the sequence lengths increase, this probability approaches 1.

Secondly, we remark that *an analytic expression for the rate of failure (= instability) of a communication-constrained feedback system of this type is not currently available*—even for scalar systems. (See [92] for additional details.) Using Monte Carlo methods for specific models, we can compute *mean time to failure* (MTTF) as a function of both the system clock rate (= sampling interval length h) and the feedback channel bit-error rate (BER). Under the assumption that the (BER) and the sampling frequency are independent, the results of one set of simulations are shown in Fig. 4. As the sampling instants get closer together (i.e., $h \to 0$), the system becomes more stable (i.e., has a smaller domain of steady-state operation). This leads to the

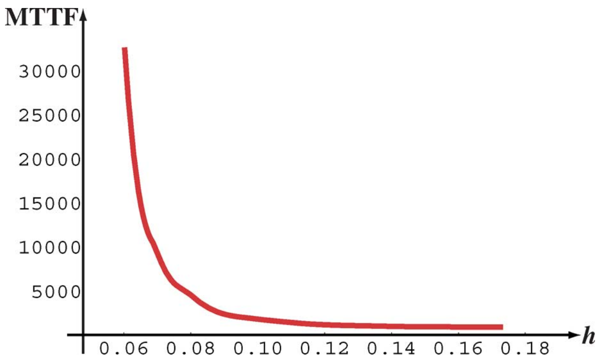

Fig. 4. *MTTF of system (8) as a function of h where $\alpha = e^h$. Simulations on which the figure is based assume a BER of 1 in 5 (0.2). As in many simple statistical models of risk and failure, we find that the standard deviation is the same size as the mean—throughout the range of sampling intervals h. It is thus not surprising that numerical simulations indicate that over a number of runs, it will frequently happen that instability occurs within a short period of time—even though MTTF is large.*

observed increase in mean time to instability. Nevertheless, as explained in the figure caption, even for high sampling rates, there is a nontrivial risk of an unrecoverable instability.

For a more detailed look at instability as a failure-mode in communication-constrained feedback control, we refer to Nair and Baillieul [92]. More generally, as the research community works to find unifying principles for operating networks of devices of all types, there is mounting evidence that formal methods for guiding both design and operation will need to take component and subsystem failures into account. While it is only a subtext in the papers featured in this special issue, many of the authors do explicitly mention *system failure* as a consideration in their research.

IV. PATTERNS AND CONSTRAINTS ON INFORMATION FLOW IN NETWORKED CONTROL SYSTEMS

A great deal of research has been published over the past five years concerning information patterns for distributed sensing and decentralized control of networks of mobile robot agents. The applications are highly varied, and the coordinated motions may be highly structured (as in the case of *rigid formations* which we discuss next) or they may have a good deal of randomness (as in the case of randomized search and surveillance algorithms—[16], [17], and also [90]).

A. Sensing Patterns to Stably Maintain Rigid Formations of Robotic Agents in Plane

The discussion in the previous section was concerned with real-time constraints on information flow through feedback channels in networked control systems. Another increasingly important class of networked control problems arises in the coordinated motion control of autonomous and semiautonomous mobile agents, e.g., unmanned underwater vehicles (UUVs), unmanned ground vehicles (UGVs), and unmanned air vehicles (UAVs). For this class of systems, the timing of control actions can be critically important, but usually one is less concerned with the data rate through a communications channel than with the patterns of information flow among the networked agents. Much of the current research in this area involves geometry in a fundamental way, and algebraic graph theory has proven to be a powerful tool for modeling patterns of information exchange among agents and relating this to the topology of formations and the stability of their motions. Directed graphs are particularly important in modeling network characteristics such as "agent i receives information from agent j," or "agent i measures its distance from agent j." The classical theory of graph rigidity has inspired new work on graphical methods for modeling parsimonious use of information, and this work has in turn led to new results regarding rigid graphs (see [54] and [55]). In [14], it was pointed out that conflicting interpretation of information in a decentralized control setting could lead to *information-based instability*. The idea is simply illustrated in the case of two mobile agents, each of which has a line-of-sight distance sensor with which it can measure the distance from itself to the other. In an ideal setting, each agent would be measuring exactly the same distance. In modeling the real world, however, noise and sensor inaccuracies must be accounted for. Label the two agents A and B, and assume (without loss of generality) that because no two sensors can be calibrated to give exactly the same readings, the distance as measured by A from A to B is greater than the distance B measures from itself to A. If the two robots A and B are programmed to move to have a specified separation, A will try to move closer to B, while B will try to move away from A (because of the difference in the measured values of the distance). Without additional compensating control, the two robots will thus push and pull each other out from any preassigned neighborhood in their shared workspace. The simplest possible decentralized control law is thus unstable if both A and B try to use independent measurements of the same quantity. There are many ways to solve this problem including information exchange with consensus algorithms (discussed below) or simply designating one of the two agents to be the *leader* and the other to be the *follower*. Using the latter approach, only the follower measures and attempts to control the value of the separation distance.

Pursuing the leader–follower idea, a number of researchers have investigated creating and controlling large scale formations in which interagent distances are held constant. Formation motions of groups of mobile agents in which all interagent distances remain constant are called *rigid*. A number of researchers have investigated decentralized control of rigid formations using ideas from the theory of graph rigidity. (See [52] and [53] for the basics of this theory; see [14], [19], [40], and [97] for applications to decentralized control of formations of autonomous vehicles.) Research along these lines has also been reported by J. M. Hendrickx, B. D. O. Anderson, and V. D. Blondel and coworkers [54] and [55] who have introduced the term *persistence* to extend the notion of *rigidity* to the case of directed graphs and to emphasize that in the directed case, the distance constraints are unidirectional.

Rigid formation motions are of interest because the position of each robot in the formation is known at each instant. To understand the challenges of decentralized control of rigid formations, we introduce a broad class of decentralized control laws for point robot systems. For any two fixed points in the plane, we divide the plane in half by drawing a *dividing line* of infinite extent containing the two points. Let d be the distance between the two points and let d_1 and d_2 be such that $d_1 + d_2 > d$. Then, on each side of the dividing line, there is a unique point which is at a distance d_1 from the first point and distance d_2 from the second. This observation suggests the use of peer-to-peer distance sensing to control mobile agents to move into formations with prescribed interagent distances. Connections between the algebraic graph theory, the theory of graph rigidity, and decentralized control designs are most easily established using holonomic point robot models, as has been done, say, in [19]. These models, in fact, provide reasonable fidelity in describing all mobile robot motions in cases where the length scales of the motions are a few orders of magnitude larger than the size of the robot itself. The control laws which are most natural in this context are called *decentralized relative distance control* laws, so named because they depend only on prescribed distances d_{ij}, selected robots labeled i and j, and the corresponding distances ρ_{ij} as measured by sensors.

In summary form, the issues are the following. Using distributed sensing of line-of-sight distance to selected peers, a group of robotic agents regulate their distances from one another. Typically, each robot will regulate its distance to a limited subset of its peers. (It could, in fact, consist of only one or two other robots.) A formation is said to be *stably rigid* if after any small perturbation of the relative distances among the robots, the formation will return to its preperturbation configuration by means of each robot re-establishing its prescribed relative distances from assigned peers. We shall call a rigid formation *isostatic* if the peer-group distance sensing pattern has the property that if any distance measurement between any two robots becomes unavailable, the formation is no longer rigid. The concept is illustrated in Fig. 5. Isostatic formations use relative position sensing in the most parsimonious way possible. The parsimoniousness of a decentralized relative distance control law with an isostatic formation avoids the possibility of information-based instability described previously; see [14], [15], and [19]. At the same time, it poses questions of robustness with respect to sensor failures. The tradeoffs between guaranteed stability and robustness to sensor failure are essential to understanding operational vulnerabilities of vehicle networks.

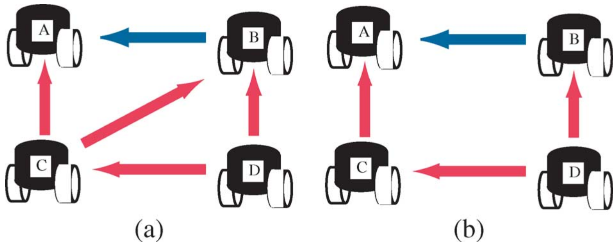

Fig. 5. ***Isostatic formation. The network of four vehicles in (a) is rigid, once leader vehicle (A) and first follower (B) are positioned. Vehicle C locates its position a prescribed distance from A and a prescribed distance from B (denoted by the red arrows from C to A and B, respectively). Robot D then positions itself a prescribed distance from B and C. As long as B measures and maintains a prescribed distance from A, and C and D measure and maintain the distances indicated by the arrows, all relative distances between pairs of robots are fixed. If some measurement becomes unavailable, as illustrated in (b), the formation is no longer rigid.***

Stably rigid formations are characterized in terms of properties of their associated *formation graphs*. A *formation graph* $\mathcal{G}$ is a pair $\mathcal{G} = (\mathcal{S}, E)$, where $\mathcal{S}$ is a finite vertex set, $\{s_1, s_2, \ldots, s_n\}$, in one-to-one correspondence with n points $(x_i, y_i) \in \mathbb{R}^2$, and E is a set of directed edges between vertices specifying the pattern of sensing. Specifically, there is a directed edge from s_i to s_j if the ith robot agent measures its distance to the jth robot agent. In terms of formation graphs, we have found that formations which are stably rigid under a decentralized relative distance control law have formation graphs which are isostatic and in which all vertices except those corresponding to the leader and first follower have out-valence equal to two. Implicit in this characterization is a constructive procedure for moving robots into formation. Starting with the leader and first follower, we sequentially add new agents to the formation by having each new agent—say s_i—move to a position located at prescribed distances d_{ij} and d_{ik}, respectively, from two agents j and k already in the formation. While not all stably rigid formations can be constructed by this procedure (formations with nontrivial cycles cannot), many of potential practical interest can. A typical formation created by this procedure is depicted in Fig. 6.

Emerging from this observation, there arises a challenging problem of scale-determined complexity in the theory of nonlinear control design. Specifically, we start with the question of how many stably rigid formations can

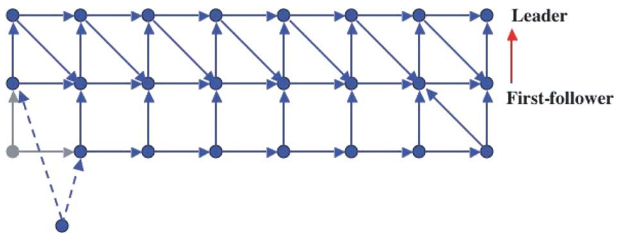

Fig. 6. *Important class of isostatic formation frameworks can be constructed from single directed edge by successively adding vertices through vertex extensions as depicted. Highly complex sensitivity of decentralized relative distance control laws to initial conditions.*

be found for n-vehicle systems. In terms of simply counting the number of possible different incidence relations associated with the isostatic formations constructed previously, the precise enumeration of cases is an open question. It is known to be exponential in n, however. For each isostatic incidence structure and given set of prescribed relative distances, it has been shown that the number of stably rigid isostatic formations is 2^{n-2} [19]; hence, the overall complexity in n is doubly exponential.

B. Consensus Problems for Groups of Autonomous Agents

Consensus problems for networks of autonomous agents have been approached from a variety of directions. A conceptually simple problem may be posed for logical graphs with labeled nodes each of whose values is updated by forming convex combinations of current values with (possibly outdated) values possessed by their neighbors. Early work by Tsitsiklis *et al.* [115] on consensus through local averaging laid a foundation for more recent applications in decentralized control and emergent behavior in networks of autonomous agents. In [117], Vicsek *et al.* report on simulations using a discrete-time model of n autonomous agents (i.e., points or particles) all moving in the plane with the same speed but with different headings. The simulations showed that if each agent's heading is updated using a local rule based on the average of its own heading plus the headings of its "neighbors," then all agents will eventually move in the same direction despite the absence of centralized coordination and despite the fact that each agent's set of nearest neighbors changes with time as the system evolves. Using techniques of the type presented earlier in [115], Jababaie *et al.* gave a theoretical explanation of this emergence of heading consensus. This circle of ideas has also been pursued in [S9] and [98], where the authors treat a wide variety of applications to synchronization of coupled oscillators, flocking, consensus in small-world networks, information fusion in sensor networks, distributed estimation, and load balancing in networks.

C. Shaping Formation Motions of Groups of Mobile Agents

While rigid formations prescribe a maximally precise relative location of each vehicle, the motion control laws for such formations are highly complex, and this complexity increases as an exponential function of the number of vehicles. Other approaches to controlling the formation shape include the Lie group-based framing of Justh and Krishnaprasad [66]. In this approach, formation vehicles move at constant velocity, tracking a prescribed curve. The intervehicle relative distances are controlled at each instant in a plane which is orthogonal to the tangent vector of the curve. Formations emerge as relative equilibria in the closed-loop system. A slightly different approach which involves organizing vehicle positions around planar curve has been taken by Lynch *et al.* [79]. In this work, mobile agents arrange themselves along a prescribed curve, and they move in accordance with directions from a set of virtual nodes which specify motions leading the agents to position themselves at equally spaced locations along the curve.

Shaping motions of groups of spacecraft using the mathematical machinery of geometric optimal control has been studied by Hussein and Bloch [58]–[60], where the objective has been to coordinate the control of groups of satellites for cooperative imaging applications. This work makes contact with both current research on optimal control of second-order systems on Riemannian manifolds and optimal coverage problems where the performance criteria are based on the physics of optics.

D. Coverage Problems for Groups of Autonomous Agents

Rendezvous problems constitute an important class of consensus problems and one major research thrust together with references to work in the field appears in [S9]. *Coverage problems* in cooperative control of groups autonomous vehicles are in a sense dual to the *rendezvous problem*. Coverage problems involve distributed control of multivehicle systems with the aim of having them quickly deploy themselves in order to be uniformly distributed in a given spatial area. In [31], the problem of distributed sensing for robotic agents acting as mobile tunable sensors is considered. Gradient descent algorithms are used to solve problems posed in terms of utility functions encoding both optimal coverage and sensing policies. In [61], coverage control of networks of mobile sensors with limited sensor range is treated and proved to provide guaranteed levels of performance even under incomplete connectivity of the network.

Numerous researchers have studied the interplay between connectivity relationships, which are well modeled using algebraic graph theory, and the dynamics of component members of the formation. Certain types of symmetries are naturally modeled using mathematical tools from graph theory and group theory, and in many cases these tools suggest the design of distributed control laws which preserve the symmetries. Work reported by Marshall and Broucke [80] explores circular connectivity and symmetry-preserving motions, and Recht and D'Andrea explore distributed control algorithms which preserve symmetries associated with nonabelian symmetry groups [101].

V. TOPICS AND ORGANIZATION OF THE SPECIAL ISSUE

The remarkably high level of current interest in what has become known as *network science* dictates that we need to be modest in claims regarding the scope of this Special Issue. Hence, we shall only say that the papers which follow report *some* of the most important work in the broad area of networked control systems. Given the mission of the Proceedings to explore topics comprehensively, we have chosen to have the Special Issue treat several topics in depth, while using this introductory paper to briefly mention other important work which could not be fit within the space of a single issue of the Proceedings. Thus, the remainder of the Special Issue is organized as follows. Section V-A contains four papers falling under the general heading of *state of the art in current technologies involving networked control systems*. The four papers treat safety in industrial networks, cooperative data acquisition by coordinated mobile sensors and large-scale experimental efforts with fleets of underwater vehicles, a large-scale experiment with an irrigation network with wireless-integrated sensors and actuators, and finally the role of networked systems in contemporary and future military applications. Section V-B contains five papers which we have grouped under the heading of *foundations of networked real-time systems*. In this section, the topics have been chosen to provide a survey of recent research on feedback control under data-rate constraints, networked control with variable channel capacity and packet drops, optimal control of networked systems with unreliable links, biologically inspired networks of certain classes of devices, and finally consensus problems in various types of multiagent networks. The final two papers of the Special Issue have been grouped in Section V-C under the heading *wireless networks—the backbone of networked control systems*. These papers treat the design of networks for vehicle tracking and other real-time applications. The final paper, on layering as optimization emphasizes modularized design and operation and at the same time suggests a mathematical approach to decomposing very large scale optimization problems that are intrinsic in networked control systems. The papers in these three sections are summarized as follows.

A. Current State of Technology of Networked Control Systems

J. R. Moyne and D. M. Tilbury, "The Emergence of Industrial Control Networks for Control Diagnostics and Safety." Networks have become a critical and pervasive component in manufacturing systems, providing connectivity from the I/O shop-floor level all the way up to the enterprise business level. Networks connecting the factory-floor information systems with the front-office systems exchange scheduling and quality data. Networks connecting machines on the plant floor carry real-time control and diagnostic data. Networks are also being used in safety systems, such as emergency stops and lockout gates. The use of networks (as opposed to traditional point-to-point wired systems) has improved reliability, visibility, and diagnosability of the manufacturing systems, in addition to reducing installation and maintenance costs. Unfortunately, network and network device performance, which of course plays a critical role in the operation of these systems, is not well understood and is rarely taken into consideration when designing these networked control systems. This paper describes the emergence of networks for control, diagnostics, and safety, and presents mechanisms for designing and analyzing network control solutions. Network performance characteristics such as delay, delay variability, and determinism are characterized. Future trends in manufacturing control networks are discussed, such as the move to wireless for all categories of data exchange. Networked control systems are a key factor towards realizing the ultimate goal of e-manufacturing.

N. E. Leonard, D. Paley, F. Lekien, R. Sepulchre, and D. M. Fratantoni, "Collective Motion, Sensor Networks, and Ocean Sampling." This paper reports on an on-going project aimed at developing a mobile sensor network which can be used in a wide variety of adaptive ocean sampling applications. There are many components to this research, and the focus here is the work on optimized data collection using networks of sensor-enabled mobile agents. While the specific application involves ocean sampling and the location and mapping of thermal gradients, the work is also applicable to mobile sensor networks and adaptive sampling problems over a number of domains. A typical domain is the Earth's atmosphere where airplanes, balloons, satellites, and networks of radars can be used to collect data for weather observation and prediction. Other applications include space-based sensing where clusters of satellites can be used with optical sensors and interferometric techniques measure characteristics of planets in distant solar systems. The paper mentions a number of such applications where a key feature of optimal sensing is the use of motion control which is optimized to make the data acquisition as effective as possible.

M. Cantoni, E. Weyer, Y. Li, S. K. Ooi, I. Mareels, and M. Ryan, "Control of Large Scale Irrigation Networks." This paper considers a control problem involving sensors and actuators which are necessarily distributed over a large and typically remote area. After introducing the problem of irrigation network management from the perspective of distribution efficiency and quality of service, the authors focus on the problem of regulating the water level along an open water channel fitted with flume gates which host sensors, actuators, and the information processing and radio resources required to participate in a communication network linking the gates and a central station. In light of the large-scale nature of the problem, and the typical noncontrol related information load on the communication network, most of the paper is devoted to the discussion of feedback control schemes that involve only local (i.e., gate-to-gate) information exchange. Analysis identifies a key design tradeoff between local performance objectives and the nature of disturbance propagation through the network. Using classical loop-shaping ideas and recent tools for structured controller synthesis, an optimal control approach is proposed for systematically dealing with this tradeoff. The results of preliminary field trials are provided to demonstrate the validity of the modeling and control design framework described.

D. Godbole, T. Samad, and J. Bay, "The Role of Network-Centric Systems in Military Operations in Urban Terrain." The last paper in Section A brings the network-centric perspective to a challenging application domain, military operations in urban terrain (MOUT). This paper, by authors from Honeywell and the U.S. Air Force Research Laboratory, focuses on a new class of assets, small unmanned aerial vehicles (UAVs), and on their use for reconnaissance and surveillance missions in cities and towns. These vehicles have limited endurance and payload capability, but when integrated within an information and communication network and an appropriate concept of operations they promise to revolutionize situation awareness for military teams operating in urban environments. The paper discusses recent developments in urban UAVs, potential areas of application in the military domain, recent research results illustrating these diverse applications, and network-oriented scalable system concepts for the near-term operational use of these vehicles for MOUT. The paper also has a motivational aspect in that its discussion of the challenges and opportunities related to obtaining situational awareness in the urban environment suggests directions for future research initiatives in networked sensing and control.

B. Foundations of Networked Real-Time Systems

G. N. Nair, F. Fagnani, S. Zampieri, and R. J. Evans, "Feedback Control under Data Rate Constraints: An Overview." The aim of this paper is to give an overview of the main theoretical ideas in the area of data-rate-limited control. In addition to limited bit rates, real communication channels may suffer from a variety of other afflictions, such as channel noise, random delays, erasures, etc., that are discussed elsewhere in this Special Issue. In this paper, the focus is on explaining the limitations imposed by a constrained data rate. After an overview of significant results in the literature, two fundamental questions are explored in detail: 1) When is a linear dynamical system stabilizable over a noiseless digital channel? and 2) What can be said about the achievable control performance in the presence of a finite feedback rate? These questions can be regarded as the control-theoretic analogues of source coding and rate distortion theory. Initially, the case of unbounded encoder–decoder memory is addressed. A universal performance lower bound capturing the effect of data rate and channel delay on performance is derived, and the quasi-separation principle for data-rate-limited stochastic control systems is explained. The effect of finite encoder–decoder memory is then explored, focusing on the fundamental tradeoffs between bit rates, mean entrance times, and contraction rates for noiseless linear systems.

J. P. Hespanha, P. Naghshtabrizi, and Y. Xu, "A Survey of Recent Results in Networked Control Systems." Several papers in the Special Issue are concerned with data losses that seem unavoidable in current wireless networking technologies. Hespahna *et al.* present results on estimation and controller synthesis aimed at spatially distributed control systems in which the operational challenges arise from the nature of the wireless communication links between sensors, actuators, and controller. The paper addresses the effects of channel limitations in terms of packet rates, sampling, network delay, and packet dropouts. Several alternative ways of addressing the problems are surveyed, and these are developed with a variety of models of the phenomena in question considered. Connections with delay differential equations and Markov chain models of packet dropouts are made.

L. Schenato, B. Sinopoli, M. Francheschetti, K. Poolla, and S. S. Sastry, "Foundations of Control and Estimation over Lossy Networks." A number of papers in the Special Issue have given an overview of today's emerging applications related to large-scale networked systems and emphasized how new mathematical tools are needed to analyze and design such systems. These papers describe original formal approaches and new results. Whereas the previous paper surveys current state-of-the-art stability analysis of networked control systems, the present paper proposes a mathematical framework to optimally design networked control systems using the common UDP and TCP protocols over lossy physical layer links. In particular, this paper discusses stability criteria and provides numerical tools to find stabilizing controllers under different communication protocols. The paper also discusses the fundamental limitations of control in the presence of limited information in the form of losses. It also shows how fundamental results in classical control theory, such as the separation principle, do not hold under some specific communication protocols. These results suggest the need for simultaneous cross-layer optimization of controller and communication protocols. This theme will be extensively revisited in the final paper of the Special Issue.

B. K. Ghosh, A. Polpitiya, and W. Wang, "Bio-inspired Networks of Visual Sensors, Neurons, and Oscillators." The paper focuses on the role of networks for sensing, encoding, and decoding—with the eventual goal of target localization, control, and actuation. In dealing with a network of mobile sensors, a typical problem is that of calibration. In order to fuse data from various sensors, the calibration problem must be solved first. The paper proposes "optimal sensor placement" as one way to address the calibration problem enabling one to rapidly fuse the associated sensor data. The techniques discussed in the paper address problems very much along the lines of the problems in [S2] wherein the distributed ocean sampling sensor data needs to be fused. Coding of the sensory data with sparse codes and principal components, discussed in this paper, also makes important contact with the ideas discussed in [S7]. If data rate is the bottle neck, it would be useful to consider a coarser representation. The price one pays is in detectability. The paper introduces the use of coupled oscillators as decoders, which again makes contact with the paper [S2]. The role of communication, packet drops, and variable delays are important areas of design that are the subject of future research in the study of networks of mobile visual sensors.

R. Olfati-Saber, A. Fax, and R. M. Murray, "Consensus and Cooperation in Networked Multiagent Systems." Multiagent systems that consist of many interacting units with low-cost embedded sensing, communication, and computational devices appear in broad engineering applications. Consensus problems in networked dynamic systems have defined a unifying theme in performing various cooperative tasks in multiagents systems—including flocking, formation control, rendezvous in space, synchronization of coupled oscillators, and information fusion in sensor networks. The present paper provides an in-depth survey of existing consensus algorithms and convergence and performance analysis for such algorithms in presence of variable network topology due to link failure or packet-loss, directed information flow, communication time-delays, and nontrivial vehicle dynamics. This paper uncovers a synergy among diverse fields of engineering and science such as control theory, complex networks, distributed computing, spectral graph theory, matrix theory, and Markov chains. The paper illustrates the concept of "cooperation" among dynamic systems via a detailed discussion of formation control for networked multivehicle systems. The role of "small-world networks" in dramatically increasing the convergence rate of consensus algorithms is also briefly discussed.

C. Wireless Networks—Backbone of Networked Control Systems

S. Oh, L. Schenato, P. Chen, and S. S. Sastry, "Tracking and Coordination of Multiple Agents Using Sensor Networks: System Design, Algorithms and Experiments." Part C of the Special Issue discusses recent research on advanced wireless networks aimed at meeting the requirements of networked control systems. In particular, this paper, which begins Part C, illustrates the main challenges in developing a real-time control system for pursuit–evasion games with the aid of a large scale sensor network. These arise from the inconsistency of sensor measurements due to packet loss, communication delay, and false detections, and from the necessity of optimal coordination of a large number of agents. Novel algorithms based on multiple layers of data fusion and on a real-time hierarchical coordination architecture are proposed and successfully demonstrated in a large-scale outdoor wireless sensor-actuator network.

M. Chiang, S. H. Low, A. R. Calderbank, and J. C. Doyle, "Layering As Optimization Decomposition: A Mathematical Theory of Network Architectures." Networked control systems in this special issue depend on the design of the underlying networks, where architectural decisions are particularly important. The "layered" protocol stack is a key manifestation of modularized network design, which has traditionally been constructed based only on heuristics. The final paper of the Special Issue surveys this emerging framework and provides a unifying analytic foundation for layered network architectures. Conceptually, it approaches the issue of distributed network resource allocation with modularized design through optimization theory and decomposition theory. The mathematical methods surveyed in this paper consist of both those discussed in other papers of the special issue (e.g., convergence analysis) and other techniques on distributed algorithms (e.g., combinations of alternative decompositions).

As with many of the other papers of the Special Issue, there is also a discussion of the implications of the surveyed theory to practical communication networks (e.g., enhanced TCP in the Internet or protocols in commercial wireless systems). A first principles approach to network design, the paper illuminates a promising synergy between the control of networks and networked control systems.

VI. CONCLUDING REMARKS

The goal of the present paper has been to introduce the reader to the field of Networked Control Systems, to provide a description of the papers that follow, to mention some notable research topics that are not covered here, and to describe important research directions. You, the reader, will be the judge of whether we have been successful. Again, it is stressed that not all aspects of current research have been covered, and we apologize to anyone who feels that topics of importance have been left out. This issue was put together over the course of two years, and it has been made possible primarily because of the significant time and effort the authors of its papers have invested. We would like also to recognize the contributions of the reviewers who helped the authors refine and focus the ideas in the manuscripts. Without their help the issue would not have been the same. Finally, we would like to thank the Managing Editor Jim Calder and Publications Editor Margery Meyer for their continuing support. ■

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