Perspective

New Vistas for Process Control: Integrating Physics and Communication Networks

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Introduction

"The field equivocally covered by the word communication permits itself to be reduced massively by the limits of what is called the context". *Jacques Derrida*

It is safe to assume that most readers of this article have had some exposure to process control and that the reach of their educational training was limited to classical chemical engineering applications. However, the ideas underlying control are applied in a much broader context than most people imagine and they contribute to improved business performance and ensure that process devices of astounding complexity perform to specification. The expanding horizons of process control now include information technology, distributed computation, new process technology, and ever more detailed descriptions of the physical world. More and more devices do not function if the onboard control system fails.

In this perspective some examples will be given of how complex control systems are designed and evolve using a glass plant, a bio-organism, business, and computation as examples. A few challenges and opportunities for R&D are reviewed. In the most minimal way possible, it is argued that the classical paradigm for process control may provide an adequate basis for a comprehensive and coherent theory for networks of distributed devices. However, it may be necessary to introduce some new tools to ensure a better conflux of communication, computation, and the physical world than we have achieved in the past.

In order to achieve this goal it is necessary to improve our abilities to model and describe the behavior of complex systems at higher levels of abstraction. It is necessary to develop control methods for diverse scales and physical phenomena, as well as find good ways to integrate these and design systems that address more diverse control objectives than has been done in the past.

Classical Program, its Strength and Limitation

Well Babbage, What are you thinking about? I am thinking that all these tables (pointing to the logarithms) one day may be computed by machinery. (Anecdote about Charles Babbage c. 1825)

The main strength of the classical model for process control, which we all are familiar with, is that it *separates the physics from the process* and allows us to develop methods independent of the area of application. A discussion of whether the object of study is a financial process, a chemical process, a booster rocket as shown on the cover of this issue, a medical device, or traffic control can be put off for later. One good example is the linear control theory that we were exposed to in the undergraduate control class. It is "context free," and issues like stability and control design can be studied independent of the physical world in an idealized framework. The main weakness of the model is that methods developed from this perspective can appear to be quite abstract and difficult to apply. Linearity, it can be argued, does not capture the essential physics of many chemical processes. Nevertheless, our experience tells us controllers based on linear theory often work very well. More importantly, we find that the insights generated from the linear theory extend far beyond what might be expected.

The *program* for process control research during the last several decades has therefore been to extend the reach of classical control to "bridge the gap" and develop more comprehensive approaches to process control to better integrate the behavior of the chemical processes and the control methods. Two somewhat different lines of attack have been pursued. One is based on fitting models to process data. This approach led to implementations of model predictive control, adaptive methods for online tuning and control of relevant identification (Rivera and Jun, 2000). The other approach develops control techniques for nonlinear models. One important contribution here was to combine model predictive control with physical constraints; another one was the development of nonlinear control theory. Significant advances were made in combining methods and making them "robust" to model errors and noise. Also, numerical algorithms were developed to solve large-scale, modeling, control, and optimization problems, involving more orders of magnitude, equations, and constraints than possible before (Albuquerque et al. 1999).

The field is now moving into nontraditional areas of application such as biomedical applications (Rao et al., 2001; Morari and Gentilini, 2001) and supply chain management (Backx et al., 1998; Perea-Lopez et al., 2001) to name a few. Present issues are centered on how to integrate information technology, and distributed networks of computers and physical devices with scales ranging from the molecular to an entire enterprise as discussed in recent *AIChE Journal* perspectives (Grossmann and Westerberg, 2000; Harold and Ogunnaike, 2000).

Examples of Process Control Systems

In order to provide a perspective on process control, it is necessary to delimit the subject and define the terms that we consider. By a *process control system*, we now understand an integrated network of computational devices, sensors, actuators, and a process whose dynamic behavior is constrained by physical laws. Thus, there are four objects of study: The *process*, the *behavior*, the *methods*, and the *context*. I give examples below of such systems to illustrate how diverse the application of these ideas can be.

During the past ten years, I have worked with PPG Inc. in Pittsburgh on developing an integrated approach for stabilization, control, and optimization of glass manufacturing processes. Sand, soda ash, and other raw materials enter one end of the plant, and these ingredients are then mixed according to the given recipe and fed to a furnace, melted, refined, and transported by fluid flow to the "tin-bath." The glass there spreads out on molten tin and cools until it is viscous enough to be lifted out as a continuous sheet. This sheet is about 1 mm thick and 9 ft wide for production of automotive windshield glass and may be more than 20 mm thick for other applications. Continuous and slow cooling after the tin-bath reduces thermal stress, and, finally, the glass is checked for quality, cut, sorted, and packaged. Scrap pieces and rejects are broken up and recycled. A very brief and interesting description of the dramatic development of this process is given by Utterback (1994).

The main objectives were to improve yield, maintain quality and stability, and reduce product changeover costs. Diverse objectives and system complexity precluded us from simply "wrapping a loop around the entire process" and applying one particular brand of control theory. We used a variety of models to find where to place new sensors, how to decompose the plant into smaller sub-sections, structure control systems, and design estimators for unmeasured variables. The control system evolved over time and continues to be refined. It now includes nonlinear and constrained predictive control, Kalman filters, adaptation, stochastic control, vision systems with pattern recognition, and discrete feedback logic. The control loops are implemented on a number of different computer platforms, integrated via local area network, and coordinated with the business system through the internet. The system has been implemented on most PPG glass plants and contributes towards significant yield improvements and improving the bottom line.

In fact, many man-made and natural control systems work well when distributed "devices" are integrated in sequence and parallel and are coordinated by the information system. Even a cursory study of a single cell organism reveals control systems that evolve and change depending on the environment and the internal state of the organism. The bio-chemical feedback loops are often so integrated with the process that it is difficult to distinguish between controller, process, and communication system. Also, the same device sometimes acts as an actuator and a sensor at the same time. New paths are added and others are deleted depending on what the sensors detect, and parallel paths may be added to achieve redundancy (Majewski and Domach, 1990).

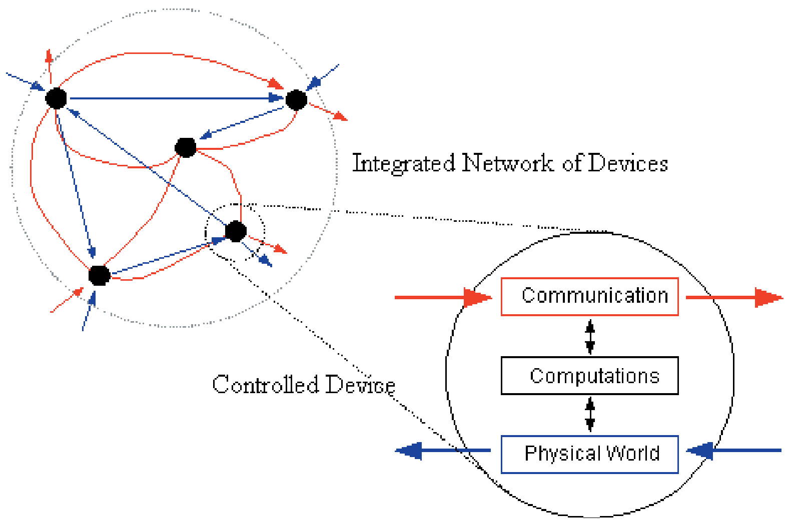

Figure 1. Process control traditionally integrates the physical world and the communication system through sensors and actuators.
The communication system is shown here in red and the physical interactions in blue. All information is accessible without delay throughout the entire enterprise via high bandwidth communication lines and wireless. Business and biological systems exhibit similar structures.

These ideas apply to organizations as well. Communication and control must be applied to maintain organizational flexibility and stabilize the supply chain dynamics so that the distribution network remains agile and able to adapt to global competitive pressures and changes in company strategy (Stern and Stalk, 1998). During my tenure as Director of R&D in ELKEM, Norway, I got exposed to a refined version of the TOYOTA manufacturing system. Control terms like the "current state," "target state," "measurable performance objectives," and "enablers" (control inputs) are important ingredients. Such tools have clear parallels with process control. Together with business to business information exchange and quality measurements like GE6Sigma, they provide mechanisms for sensing and acting in real time (Harold and Ogunnaike, 2000).

Architecture, flexibility, and distribution of work also play critical roles in complex software development and dynamic simulation over the Web. Protocols for integration are defined so that the system can develop and expand rapidly using diverse and distributed resources. The software developer can focus on the task at hand without having to reconfigure the entire system each time a new software module is developed. One line of current control research focuses on distributed transportation systems, networks of wireless communication systems, and mobile units (Kumar et al., 2001).

Figure 1 illustrates some of the common features of networks of control systems discussed very briefly above. The "devices" consist of computational units with sensors and actuators. These units provide the link between the physical world and the information system. Such devices will often be interchanged and redesigned, or they may move around as they do in traffic control and transportation. New devices can be added while connections between devices can be emphasized or made marginal in order to maintain "stability" and improve performance. Process control theory provide powerful methods that can be used to analyze and design such complex systems.

Reduction into Sub-Problems

The task of designing, analyzing, and operating complex networks and organizations requires a reduction into smaller and more manageable sub-problems. In this section I will review some separation principles, and I propose that physical and time scales can be linked. In the next section we use a simple example to illustrate that caution must be exercised when we put the parts together.

The literature abounds with articles with titles of the type: "... control of ..." where the dots correspond to method and unit process, respectively. This approach has been exceedingly useful and lays the foundation for plant wide control—we put the units together into plant sections and plant-sections together into factories. Factories with raw-material sourcing and distribution networks combine into enterprises that connect with other enterprises. The idea of separation can be carried out at smaller scales too, leading to the continuous hierarchy which Grossmann and Westerberg (2000) call the "chemical supply chain."

So, physical size can give separation of scales. Another intuitive and very powerful separation principle emerges for dynamical systems with fast and slow dynamics. Cascade control provides one example. The control here is separated into a fast inner loop and a slow outer loop to give good disturbance rejection. These techniques can be applied to nonlinear systems using averaging or perturbation akin to the boundary layer methods used in fluid mechanics. Such methods have been used for analysis of adaptive control systems, lumping high-order systems, and, more recently, design of low-dimensional controllers for distributed parameter systems (Christofides, 2001). Time-scale separation is routinely used to motivate plant wide control system structure, it has been used to study systems with recycle, and it turned out to be critical for the glass application described above. The importance of these ideas lies in the fact that they allow us to "average out the details" and focus on time scales of interest.

Time scales and physical scales are often commensurate in the sense that small systems may have fast dynamics and large systems, and organizational units have slow dynamics.

Thus, we may relabel by time the abscissa in the figure provided by Grossmann and Westerberg (2000), starting at the pico-second level for molecular simulation to a year or more when we consider plant construction and complex organizational changes like mergers and acquisitions.

Possibly, the most important and useful separation principle in control was proposed by the late Herb Simon of Carnegie Mellon. He showed us that in some cases the tasks of control and state estimation can be done independently of each other. The principle is pleasing not only because it simplifies algorithm design and reduces computational effort, but it also justifies teaching process identification and process control as separate courses. Simon's separation principle also motivated the development of "certainty equivalence" adaptive control. In this approach the process model is estimated from data online and it is then used to update the controller.

Our paradigm for computing was established when John von Neuman suggested that software and hardware should be kept separate in order to develop a general purpose "thinking machine." The idea of keeping these entities separate was not obvious at the time, but it was absolutely critical for the rapid development of hardware, software, and the internet. Almost all the computational methods that we use for systems analysis, control system design, process simulation, and optimization rely on the architecture envisioned by von Neuman. This separation does not work well for parallel and distributed computing, however. Progress here has been much slower and more hap-hazard than hoped for since software must be tailored to a particular hardware architecture and application. In the Dept. of Chemical Engineering at Carnegie Mellon we are currently studying these issues in the context of statistical mechanics, large-scale optimization, and dynamic simulation using an expandable Beowolf cluster of 64 parallel processors.

Time-Scale Decomposition and Networks of Devices

...no gluing together of partial studies of a complex nonlinear system can give a good idea of the behavior of the whole.

Murray Gell-Mann

It is not easy to go from a single to a multiprocessor environment without considering the context. Adaptive control, which was researched very actively in the 1980s, provides another example of how difficult it may be to connect devices. Even as a proponent of adaptive control, I have to admit that the approach has so far not lived up to its early expectations in the process industries as a way to automatically tune and maintain diverse control loops. It was found that instead of converging, adaptive systems generate small amplitude chaos and unpredictable bursts (Golden and Ydstie, 1994). This type of behavior could not have been predicted from the study of separate units—these are based on linear theory. The chaotic bursting arises from an exchange of stability. The issue has been studied extensively using time-scale separation, and new algorithms have been developed that overcome these problems. The most successful implementations decouple estimation and control so that the timescale for estimation is well separated from that of the controller.

Adaptive control demonstrates that unexpected dynamic behavior may result when simple devices are connected and time-scale issues are ignored. Many other examples demonstrate the same characteristics in one way or another. In robust control there is an interplay between what is modeled and what is not modeled, and we achieve stability when the unmodeled dynamics are fast, relative to the response time of the controlled system. The dynamics of plant-wide control systems are often dominated by the recycle units rather than the individual units. Too aggressive control gives demand amplification in supply chains. Bottlenecking in communication and queuing systems provides yet other examples where time-scale decomposition and averaging can be used to analyze performance and design control strategies.

The natural way forward is to design devices so that changes impact the static and dynamical performance of the system in ways that are easily predictable. This leads into a discussion of large-scale systems theory. Generally speaking, such systems can be modeled using electrical components like resistors, capacitors, and inductors. Passive devices of these types can be connected with other passive devices, and stability and some performance issues can be addressed without ever having to analyze the entire system. The keys to these developments are the conservation laws, and dissipation which gives stability. The connection with process systems and through the first and second law of thermodynamics is now imminent.

Several failed attempts have been made to link passivity with thermodynamics in order to develop a network theory for distributed chemical systems. Total energy and mass are conserved quantities, so these play the role of charge. The remaining problem is to define a function that captures the dissipation. Trivially choosing entropy cannot work. The negative of the entropy is not bounded from below.

We have made some progress in linking passivity and thermodynamics by using the concept of *available work* as an entry point (Ydstie and Alonso, 1997). The process systems is represented in this approach as a gradient system with a Riemannian structure, and devices are connected and exchanged using Dirichlet boundary conditions. Briefly, this implies that all flows should be the result of potential differences much in the same way as current is the result of a voltage difference. We have also made the observation that we achieve minimum entropy production along paths that solve Euler Lagrange equations. Along such paths, the process behaves as a Hamiltonian system, which has a Symplectic, rather than Riemannian, structure. This observation allows to conclude that classical irreversible thermodynamics solve quadratic programming problems similar to a neural network. Thus, we have formally connected thermodynamics, nonlinear control, optimization and large-scale system theory.

Expanding R&D

Even a cursory reading of past *AIChE Journal* perspectives reveals that most research in chemical engineering touches upon control systems design in one way or another. In some cases the control component is minor and in other cases it is critical to the completion of the program. Lanny Schmidt et al.'s (2000) perspective on new ways to produce traditional chemicals falls into the latter category since it requires operation of unstable, partial oxidation reactors. We do not have good theories for control of unstable systems and, as Gunther Stein stated in his 1989 Bode lecture, we never will. Safe operation of such reactors requires good integration of physics, control methods, sensors, and actuators to prevent runaway. Very unfortunate accidents continue to happen because subtleties are missed.

A completely different class of control problems, but equally critical, was raised by Robert Langer (2000). He discussed, among other control related issues, miniature devices that integrate actuators, sensors, and chemical processing. The control problems associated with the device itself can be challenging. Unimaginable opportunities loom when such devices are included as actuators in larger control systems and are manipulated by wireless.

Yet, other classes of control systems and dynamic behaviors emerge when we manipulate the structure and properties of multiphase fluid flow (Sundaresan, 2000), granular materials (Ottino and Khakar, 2001), and microscale, spatially distributed reactions (Wolff et al., 2001). Network design and stability are important in the field of biomedical engineering (Phalakornkule et al., 2001), and evolution can be directed and accelerated by application of feedback control (Moore and Maranas, 2000). There are also important issues to resolve in the design of systems that infer and control microstructure and shape. Patience and Rawlings (2001) provides an example of application of these ideas to crystal growth.

Many challenges remain in the traditional area of control. Examples include the integration of control and business systems, integration of process design and control, and the integration of plant wide control, process operations, and real-time optimization (Ogunnaike, 1999).

Many control research groups, as indicated above, are working on a range of new applications. We attack complex distributed systems with multiple objectives and many constraints, including life and death issues that come, for example, in medical applications. We are finding that the tools that have been developed for process control are powerful and practical indeed. We are also finding that the tool chest is quite complete and the insights that these tools provide are precise. The main challenge now is to integrate control methods, and process and information systems, so that these act in concert to achieve a desired response in a given context. The integration of such tools is not trivial, and requires extensive discussions in multidisciplinary groups. In the PPG examples this included managers, engineers, and plant personnel. The upside was that we got far more adaptable and profitable process behaviors than we initially expected.

Looking ahead, it does not seem too farfetched to envision that process components will be thought of as embedded "plug and play" devices that include physical hardware, dedicated computational resources for process control and data-reconciliation, simulation software, and process models so that we can evaluate scenarios in a distributed, model predictive environment. Such units will have widely different scales, but standard interconnects towards other physical devices and the Web.

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