Ports and Parts

Control is the science of interconnection and the technology of integration and informed interaction. What this means is that components have meaning and value only when they are interconnected and communicate with other components through the transmission of energy, material, or information. Whether this interaction occurs through inputs and outputs or—as Jan Willems has shown—through ports and terminals, interaction can give rise to subtle and complex behavior. You and your car are complex amalgams of interacting parts. For engineering purposes, interaction is about integration—ensuring that the parts work together to make a functioning whole. When one or more parts can compute, reason, or think, interaction involves informed action. Together, these phenomena are what control is about.

But interaction can be subtle and surprising. Why is that? Consider two chemicals, each stable and nontoxic. However, a mixture of these materials may be explosive or poisonous. This situation is not too different from the feedback interconnection of two asymptotically stable systems. The novice to our field is amazed that such an interconnection could be anything but stable; yet, despite their innocuous nature in isolation, each system manages to bring out the worst in the other.

Since two subsystems can interact in surprising ways, we can expect even more surprises in systems consisting of a large number of possibly different types of interacting subsystems. This is dimensionality. For example, plants and animals that share an ecosystem interact in competitive and cooperative ways. This is nonlinearity. Each subsystem vies for space, light, and nutrients, light, with diverse and specialized strategies for survival, maturation, and reproduction. Time scales range from weeds to oaks. Interactions may be weak or strong, two way, or multiway. We cannot understand the overall system without understanding these interactions. This is interconnectivity.

Control, as informed action and intelligent interaction, depends on knowledge, and knowledge resides in models and data. A model is an intellectual construct, usually validated—or at least not invalidated—by data. Data (in)validate models, and models give meaning to data. They are opposite sides of the same coin. But all data are noisy, and all models are erroneous. This is uncertainty. Dimensionality, uncertainty, and nonlinearity are the building blocks of complexity; interconnectivity is the mortar.

Interconnected systems found in nature and social systems are self-assembling, where diverse components may be juxtaposed by happenstance and the system evolves on its own, unscripted accord. If the self-assembly is successful, resulting in a smoothly operating system, then the outcome is astonishing because it represents—in the words of David Angeli—robustness in the face of total uncertainty. The resulting web of interaction challenges the traditional approach of reductionism, which seeks to disentangle the mass of evolved loops. When such systems are altered, either purposefully or inadvertently, the effects are often unpredictable. When an interloper shows up or an agent becomes extinct, a self-assembled system may operate smoothly or chaotically or it may simply crash.

But technological systems are not self-assembling; we architect a system, specify the components, and constrain the interactions. This is the problem of integration. Traditionally, systems were composed of largely passive—if not static—components, combined in a hierarchical manner. A car from the 1960s is a good example. Nowadays, a

Dennis Bernstein and Susan Kolovson and their sons Sam (left) and Jason.

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car may have thousands or even millions of lines of code embedded in its numerous subsystems responsible for braking, engine operation, and interior comfort. Deterministic components confined to hierarchical architectures can simplify the analysis and ensure smooth operation, but strongly interconnected systems involve components that make local, unpredictable decisions and communicate with other components at all levels.

The systems view of the world helps us appreciate why a clock is something more than the sum of its parts and why timekeeping is an emergent property of a collection of gears and springs. Even more so for a mouse, which can repair and duplicate itself and is more difficult to assemble than a clock partly because it has a vastly greater number of parts. But what does it mean for the whole to be greater than the sum of its parts? Is this a question of science or philosophy or even theology? At least we can say that the clock is the creation of another system that itself is more than the sum of *its* parts. Like Pinocchio, the clock is the sterile creation of the clockmaker.

Norbert Wiener described humans as persistent patterns that resist local increase in entropy. The physical components of the body are transient and subservient to the operating plan of the system. Imagine that you replaced a different part of your car every day of the week. The "car" would persist, and it would never wear out. The human operating plan persists due to countless feedback loops that assimilate material and perform maintenance and repair; the car persists due to its bolts and mounts, which represent rudimentary feedback, or at least—again in Jan's terminology—variable sharing.

"Control" of a densely interconnected system is an unrealistic expectation. Control is informed interaction, but the effectiveness of informed interaction is limited by dimensionality, uncertainty, nonlinearity, and interconnectivity itself. Ecosystems, like chronic diseases, cannot be controlled in the sense that we think of when a governor regulates the speed of an engine. Let's not forget that controllability means that we can bring the entire state to a desired point at a chosen time, but not that we can keep the state there, much less follow a specified state trajectory. A weaker notion of "manageability" may be more appropriate than controllability in all its shortcomings.

Dennis, Amy, and Gary Bernstein.

Which somehow brings me to learning. The construction of models and the recording of data are attributes of learning, but what *is* learning? In simple terms, learning is uncertainty reduction; I suppose this is the case when a child learns to jump rope. But learning can occur at many levels, and we certainly don't know *how* things are learned in terms of data and models. Learning begins with fog and ends in crispness, when the right answer emerges from a set of possibilities.

Without doubt, learning depends on feedback, but not all feedback is about learning since much feedback is mindless interaction, and much learning is rote. An adaptive controller is a controller that learns. An adaptive controller is a feedback control law that does not sacrifice performance for uncertainty—it not only interacts with the plant but learns from that interaction. Learning is self-adjusting feedback, that is, meta-feedback.

SOME CHALLENGES

The systems and control discipline presents innumerable challenges and opportunities that impact all facets of science and technology, from deep intellectual problems to mundane technological demands. I've already alluded to some of these intellectual challenges, such as understanding the implications of interconnectivity, the limits of reductionism, and the meaning of learning. On a more concrete level, I'll mention three problem areas in systems and control theory.

Observers and Estimators

Models can be used to enhance the value of measurements. This is what an observer does when measurements of a state are used to estimate other states. By recursively estimating states that are not directly measured, an observer creates synthesized measurements from real measurements. An observer is a closed-loop system that resides within a computer simulation, as distinct from a physical closed-loop system. In addition, a stochastically optimal observer—such as the Kalman filter—can provide state estimates that are more accurate than the noisy measurements provided by the sensors. In effect, an estimator is a model-based filter that adds value to data.

Aside from dissipativity-based techniques, most nonlinear control methods require knowledge of all system states. When full-state sensing is not available, it becomes necessary to rely on nonlinear observers and estimators in the hope that some kind of separation is feasible. Aside from control, nonlinear estimation is needed in numerous applications. The extended Kalman filter, based on linearization of the dynamics, is most akin to the classical Kalman filter and its Riccati-equation implementation. However, even for linear systems, equivalent results can be obtained by implementing an estimator based on "particles," that is, copies of the dynamics with different perturbed parameters, inputs, and initial states. The unscented and ensemble filters and their variants suggest the richness of this approach and demonstrate that Riccati-based filtering is not the way forward for nonlinear systems, especially for systems modeled by large computer programs rather than equations of motion. Just as Wiener "missed" the Riccati-based recursion, Kalman missed particle-based filters, which are more effective for nonlinear systems than filters based on linearized models and Riccati equations. Additional techniques include propagation of non-Gaussian distributions and numerical solution of the Fokker-Planck equation. Nonlinear estimation remains an area of extreme importance and deep challenges.

Decentralization

Control systems often must operate under communication constraints, which affect the ability to transmit sensor data and actuator commands in a timely manner to remote locations. This requirement is reinforced by the trend toward wireless, possibly multihop, communication networks. Communication delays constitute phase lag, which can be accommodated—albeit with degraded performance—when the delays are known but may cause instability when the delays are unknown. The lack of communication channels between sensors and actuators necessitates decentralized control, where multiple controllers operate simultaneously and without the benefit of direct interaction. The classical control paradigm is one plant, one controller, but decentralization implies one plant subject to the action of many controllers, or even a collection of coupled plants subject to the action of many decoupled controllers. Informed action in these cases is at best partial since each controller has limited knowledge of the structure of the plant and its controllers.

Decentralization presents a vastly important aspect of the control of real-world networked systems composed of interconnected subsystems, such as swarms of vehicles with limited communication links. Communication constraints preclude centralized control, and the objective is to implement independently operating controllers that can nevertheless collaborate to complete tasks cooperatively. Despite its challenges, the ideal of fully decentralized adaptive control can potentially fulfill the dream of highly reliable control, where the failure of one controller subsystem or one node in the network is automatically compensated by the remaining controllers. Fault-tolerant, decentralized control systems for large-scale interconnected systems presents a critical and necessary technology for emerging applications.

Large-Scale Systems

Large-scale systems, with thousands or millions of states, are increasingly common in control and estimation applications, such as flow control and weather forecasting. Models of this scale are not directly amenable to "centralized" model reduction since the scale of such models precludes the ability to manipulate them as a whole. Computation is unavoidably parallel, and numerical runs require days or weeks rather than minutes. Hierarchical models composed of layers of submodels are essential, but the task of verifying the fidelity of such models is likely to be a never-ending endeavor.

PASSING THE TORCH

With this issue of *IEEE Control Systems Magazine* (*CSM*), I officially pass the torch to my successor Richard Braatz. Richard will be the sixth editor-in-chief (EIC) of this magazine since its inception in 1981, continuing the tradition begun by my predecessors Mo Jamshidi, Herb Rauch, Steve Yurkovich, and Tariq Samad.

I am confident that Richard will raise *CSM* to further heights of excellence. Richard is highly accomplished in all aspects of our profession—as a researcher, educator, and practitioner of control system technology. His expertise in process control will swing the pendulum of EIC experience from aerospace to process control.

Regardless of the "home field" of the EIC of this magazine, *CSM* is committed to the widest and most inclusive coverage of all applications of systems and control. This philosophy reflects the inherent nature of our field, namely, that systems and control is fundamentally an interdisciplinary endeavor. Those who savor interaction with diverse disciplines—or simply cannot make up their minds about whether they prefer robotics or fusion—are attracted to the ideas and techniques of this multifaceted field.

While Richard will be ably assisted by the *CSM* Editorial Board, the quality of *CSM* is only as good as the articles that are submitted. This is the role and responsibility of the *CSM* readership. I encourage you to contact Richard with your ideas for future submissions.

The 51 issues of *CSM* that I've had the privilege of editing have provided—I hope—a window into what we do as a community as well as our motivations and aspirations. *CSM* has covered applications ranging from fusion to aircraft to welding to motors to waste incineration to batteries. We've also covered undergraduate education, glassmaking, delay systems, friction, active safety, spacecraft, walking robots, flexible structures, atomic clocks, optical calibration, inertial stabilization, weather forecasting, hybrid dynamics, control over networks, motorcycle dynamics, and much more.

I would also like to acknowledge all of my fruitful interactions with past IEEE Control Systems Society (CSS) presidents, from Len Shaw, who originally appointed me to this position, to those whose "President's Messages" I had the opportunity to read in advance, namely, Cheryl, Doug, Mark, John, Ted, David, Tariq, Roberto, and Rick. It was a privilege to serve under such outstanding leaders.

A crucial component of all publications, especially *CSM*, is the editorial board. The associate editors contribute anonymously by reading articles, soliciting reviews, and making recommendations. The corresponding editors invite potential authors to contribute to "Applications of Control," while the book review editors keep us informed of new texts. I am grateful for the contributions of all the members of the board who have served during the last eight and a half years.

I especially wish to thank the authors and reviewers of *CSM* articles that were published during my tenure. I also thank all of the members of our community who agreed to share their thoughts and wisdom in interviews and reminiscences. Their contribution helped to enrich *CSM* and its readers.

The quality of a publication such as *CSM* depends strongly on the efforts of IEEE personnel. I'm grateful for the support of the IEEE publications staff and their contribution to *CSM*. Richard can look forward to this invaluable assistance.

Finally, I thank all of those who helped with the magazine in unofficial ways. Siblings Amy and Gary read and critiqued numerous editorials, lending ideas and offering frank criticism, all of which led to more thoughtful essays. Sons Sam and Jason Bernstein contributed to many of the "Random Inputs" columns, through refinements of ideas and artwork. And last, but certainly not least, I wish to thank my wife Susan Kolovson for her invaluable assistance on the magazine and her infinite patience while I spent untold days and nights seeing *CSM* through to publication. These are debts I cannot repay, although I will certainly try.

Dennis S. Bernstein

Mission

The CDC is the historical meeting place of the CSS. It is a place to see and be seen; a place to grow, to nurture, and to learn; and it is truly a homecoming for many. It is an international conference hosting Society meetings such as the Board of Governors. It is a meeting widely recognized within the control community as a high-quality conference where people go to meet old friends and new colleagues. It is where a great deal of business gets accomplished, woven within a tapestry of technical and social interactions. It is where new researchers make their debut and established veterans offer words of wisdom and inspiration. It is where the Bode lecture is delivered and the Society awards ceremony is held.

—From Cheryl B. Schrader and Mark W. Spong, "The IEEE Conference on Decision and Control, Tracing CDC History," *IEEE Control Systems Magazine*, vol. 24, pp. 56–66, Dec. 2004.

Nostalgia

The CDC grew out of a series of meetings known as the Symposium on Adaptive Processes (SAP), the first of which was held in New York City in June 1962 in conjunction with the Joint Automatic Control Conference (JACC). The JACC, in turn, was a precursor to the American Control Conference (ACC). At the time of the first SAP, Yuri Gagarin and John Glenn had recently become the first humans to orbit the earth, the Beatles were unknown outside of Liverpool and Hamburg, and the Cuban missile crisis was about to begin. We were, of course, in grade school and largely unconcerned with such events. We, along with many others, have grown up together with the CDC through Vietnam, Watergate, détente, the fall of communism, and the rise of terrorism. We have formed close friendships, established professional contacts, and witnessed the passing of several colleagues and friends.

—From Cheryl B. Schrader and Mark W. Spong, "The IEEE Conference on Decision and Control, Tracing CDC History," *IEEE Control Systems Magazine*, vol. 24, pp. 56–66, Dec. 2004.