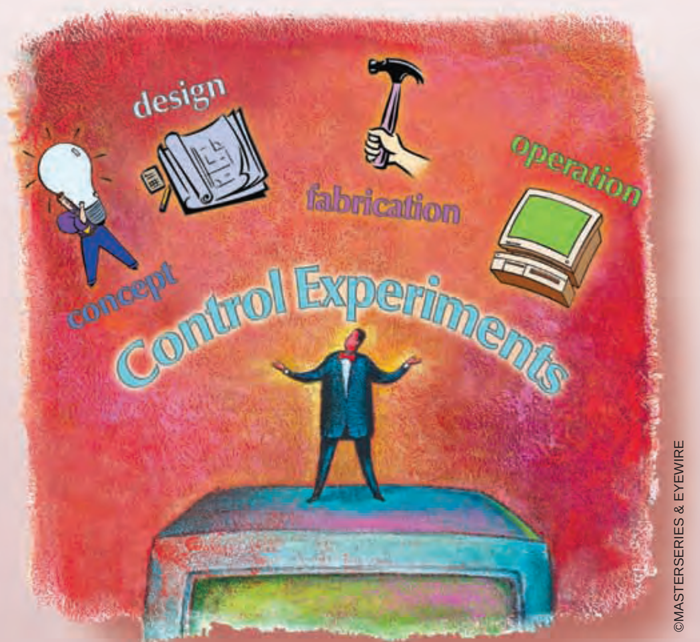
Experiments for Control Research

Introduction to the special section.



By Dennis S. Bernstein and Jacob Apkarian

In the past decade, there has been an explosion of activity in what we commonly call control experimentation. Even without a definitive statement of what constitutes a control experiment, there can be little doubt that the implementation of control theory on control hardware can have only a positive impact on control engineering and control education. Since the ultimate goal of control theory is to enhance the performance and reliability of operational systems, control experiments provide a valuable link between theory and practice.

The articles in this issue were selected largely for their contribution to improving our understanding of the role of control experiments in control research. Consequently, each article includes perspective on the conceptualization, design, construction, and operation of laboratory experiments. In addition, the authors of each article make a conscious effort to discuss the effect of their experimental activities on the development of control ideas. Although there is less emphasis on how these experiments might impact control practice, it is only a small step to drawing conclusions in that direction as well.

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Before introducing the articles in this issue, we will use this opportunity to provide some philosophical remarks on the meaning and role of control experiments in control research. The following discussion represents a synthesis of many points raised in the individual articles as well as our personal experiences in developing and operating control experiments.

Experiment Paradigms

To place control experiments in perspective, let's consider two disparate fields of science, namely, astronomy and biology. In astronomy, an experiment is essentially data acquisition. While the astronomer must decide where to look, what kind of data to collect, and how to interpret it, there is no opportunity to influence the behavior of the system. This is an *output-only* experiment intended solely for system identification (see Figure 1).

On the other hand, in a biology experiment it is possible to modify the behavior of the system through controlled inputs such as chemical concentrations, temperature, and other physical variables. The system of interest is natural, although it is often modified to some extent, for example, through gene manipulation, to obtain further insight into its features. These modifications can be viewed as generalized inputs for identification and control objectives.

Although there are natural-system experiments that are of interest to engineers, such as the characterization of materials, the focus in engineering is largely on systems that are artificial, those designed and fabricated by conscious effort. These systems can be examined experimentally through controlled inputs and data collection.

Since engineering focuses on artificial systems, it would seem that experiments are not necessary. However, experimentation and testing of engineered systems is common practice in all branches of engineering. We provide a rationale for the need for engineering experiments within the context of control engineering after we distinguish between technology-driven and system-driven control experiments.

Technology-Driven Versus System-Driven Control Experiments

There is no doubt that the implementation of any control system involves experimentation. Such experiments may involve hardware testing, noise measurements, margin estimation, and numerous other aspects that affect control system performance. It is therefore reasonable to assert that control experiments are as old as control technology itself. These experiments are usually limited in scope, however, in the sense that they are directed at the characterization and implementation of specific hardware for a specific purpose.

More generally, a control experiment may be performed without a specific hardware implementation in mind. It is therefore useful to make a distinction between *technology-driven* control experiments and *system-driven* control experiments. Control experiments aimed at the constitutive technologies are technology driven. For example, the development of materials and devices for control actuation can be viewed as technology-driven control experiments. For such experiments, the specifications and performance of the technology are of primary interest. Such specifications might include the bandwidth, force, and power provided, for example, by traditional electromagnetic actuators or emerging smart materials.

In contrast, the last decade has seen considerable growth in a new genre of control experiments that are system driven. In a system-driven control experiment, the primary concern is not the absolute performance of the hardware components per se. Rather, the objective is to understand the tradeoffs among hardware constraints, plant properties, and achievable performance from a systems point of view. These tradeoffs depend on the accessibility and authority of the chosen control hardware. Moreover, the mutual interaction of instability, nonlinearity, dimensionality, control-loop coupling, uncertainty, and noise determines the difficulty of the control design and implementation.

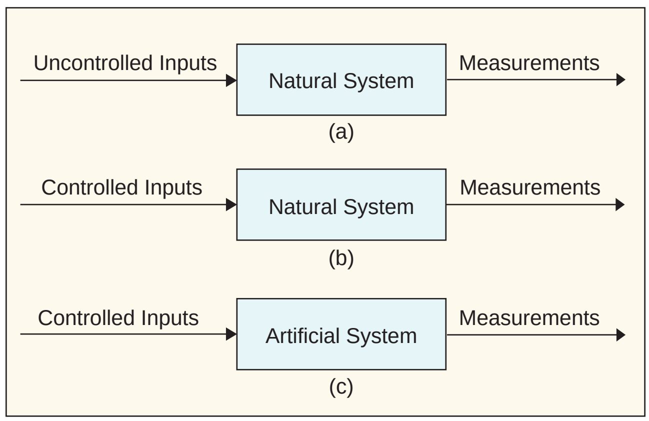

Figure 1. *Experiment paradigms. Each of these figures represents a paradigm of an experiment under different operational conditions. (a) Output-only experiment. In this case, the experiment involves data collection but without the ability to choose the inputs to the system. In addition, the system is natural, that is, it has not been modified by conscious effort. This kind of experiment, intended solely for system identification, is representative of astronomy. (b) Input-output experiment. In this case the experiment involves the specification of inputs as well as data collection. As in the previous case, the system is natural. This kind of experiment is representative of biology, where identification and control are of interest. (c) Input-output experiment for an artificial system. As in the previous case, the experiment involves the specification of inputs and data collection, but the system has been designed and fabricated intentionally. This kind of experiment is the paradigm for engineering experiments, in particular, control experiments.*

While the control experiments described in this issue involve real hardware, they are all, in our opinion, ultimately system-driven experiments. None of the experiments purports to develop new sensors or actuators or attempts to validate the performance of new technologies as an end in itself. Rather, using specific technological systems as a venue, each article attempts to gain insights that transcend the specific technological application. These insights validate existing ideas and motivate new ones, thereby impacting control technology well beyond any one particular application.

Since the ultimate goal of control theory is to enhance the performance and reliability of operational systems, control experiments provide a valuable link between theory and practice.

Developing System-Driven Control Engineering Experiments

As already discussed, engineering experiments are generally based on artificial systems that have been fabricated by conscious effort, although fabrication is only one aspect of a control engineering experiment. In our view, the overall design process involves four interrelated phases: conceptual, design and fabrication, surprise, and performance. Although these phases apply to engineering experiments in general, we focus on system-driven control engineering experiments.

A control engineering experiment begins with the *conceptual phase*, where the system-theoretic objectives of the control experiment are formulated. For example, if the objective is to investigate multivariable linear control, then one may conceive of a control experiment with highly coupled inputs and outputs with plant dynamics that are reasonably linear. Active acoustic noise control provides one possible venue for such investigations. On the other hand, if the objective is to investigate nonlinear control of underactuated systems, then one may conceive of a single-input, single-output plant with multiple internal states and, perhaps, an uncontrollable linearization. Mechanical systems with kinematic and geometric nonlinearities provide a venue for such experiments. In these examples, system-theoretic objectives drive the hardware venue, although it often occurs that a specific application or technology suggests system-theoretic research objectives.

The next stage of development is the *design and fabrication phase*, where the experimental concept is realized in hardware. In this phase the available sensors and actuators often determine the experiment scale. Since the experiment is system driven, the spatial and temporal scales need not satisfy absolute specifications, but rather the sensor and actuator sizing can be chosen based on the availability of affordable commercial components.

The next phase is of crucial importance in clarifying the role of control experiments. This is the *surprise phase*, where the fabricated system exhibits features that were either unexpected, unintended, or unmodeled in the conceptual and design phases. We can view these features as natural characteristics of a fabricated system. For example, the fluid dynamics in the experiment designed by d'Andrea et al. are present without any special engineering effort and they appear in all of their infinite complexity. On the other hand, the stiction effects encountered in the earlier realizations of their apparatus were not of ultimate interest and thus were designed out of later hardware versions. Every control experiment will exhibit unmodeled if not unmodelable effects. The conceptual framework for a control experiment may thus evolve as the unexpected effects are better understood and adopted as relevant research objectives.

Last, we have the *performance phase,* wherein the experimentalist is able to operate the control experiment under a rich variety of conditions to obtain extensive experience with controller implementation while gaining insight into system properties. For example, the experimentalist can impose artificial constraints (such as sensor and actuator saturation or deadband), feign uncertainty (ignoring parameter information or imposing plant changes), degrade sensor accuracy (through artificially generated noise), constrain controller communication channels (to impose decentralized control), and consider a virtually unlimited class of simulated control engineering challenges. For some experiments, the control challenges are inherent to the system design, and challenges emerge naturally as the experimentation objectives become increasingly ambitious. The RABBIT robot discussed by Chevallereau et al. has this property due to instability and underactuation coupled with the future goal of controlled running.

The concept of a performance phase within a control experiment is unique to engineering and is crucial to control engineering. In virtually all applications, an experiment is set up to collect data on a specific question, and the experiment is subsequently torn down or cannibalized. However, in control engineering, an experiment that can remain operational for perhaps years can provide researchers with the opportunity to implement novel control ideas as they're developed. In short, a control experiment plays the role of the enduring piano in your living room on which you perfect your performance skills over the course of time by continual practice.

Overview of the Special Section

The introductory essay by Bernstein highlights the challenges one faces when setting up a control research laboratory. The article discusses the tradeoffs associated with building your own experiments versus buying experiments from commercial vendors. Many other topics are covered to help guide the novice through the challenges of developing a control laboratory for research.

The article by Alleyne et al. points out important lessons associated with control system experiment design. The authors discuss the relevance of modeling within a control-oriented framework, the importance of specific goals and performance criteria, the consideration of actuator saturation and sensing limitations, and, finally, the benefits of serendipity on research. These topics are presented within the context of four varied systems derived from the automotive and heavy machinery industry areas. The article emphasizes the distinction between control technology experiments and control-validation experiments, which correspond to technology-driven and system-driven experiments discussed earlier.

Motivated by the desire to develop and test new algorithms for controlling interconnected systems, Fowler and D'Andrea develop a formation flight experiment. Within the context of this special section, the authors describe the design decisions and potential pitfalls encountered while designing this experimental system. One of their main requirements, atypical of standard engineering practice, is to deliberately design a system that is hard to control. Some system parameters, however, are constrained by factors such as size, weight, and power, thus limiting design choices. These constraints lead to the introduction of further nonlinearities and undesired phenomena not originally intended, corresponding to the surprise phase. This process motivates the design of subsequent generations of the experimental testbed to systematically tailor the desired characteristics.

The article by Bernstein et al. focuses on the development of a shape change actuation testbed for precision attitude control as an alternative to traditional thrusters and wheels. The testbed presents challenges due to the fact that the control authority is weak, rendering the effects of unmodeled disturbances and nonlinearities significant. The authors discuss the issues faced when developing the hardware as well as the unexpected challenges arising due to gravity, saturation, and stroke limits. Some of these challenges result in opportunities to investigate and develop new control strategies.

Chevallereau et al. present work driven by the goal of designing a walking robot of utmost mechanical simplicity that still exhibits the key phenomena that make the control of walking a largely open problem from the control design and analysis perspective. This simplicity in design also helps to balance budgetary constraints against performance and robustness. The article discusses the rationale and design for a simplified mechanism that has no feet and yet is able to walk in a provably asymptotically stable manner. The design and construction of the mechanism is carried out in parallel with the development of new ideas on how to control biped robots; the experiments are serving to explore these new ideas on a real robot.

Conclusions

Control experiments are now reaching a level of sophistication, ease of use, and ubiquity that was undreamt of a decade ago. Yet, this level is only the beginning of what we can expect to see as researchers continue to merge theoretical research with laboratory implementation. For control research, experiments force developers of control theory to confront details that are ignored in standard analysis, thereby motivating more comprehensive and, thus, more useful techniques. These experiments also provide a venue for testing and demonstrating new ideas, thereby understanding their strengths and weaknesses beyond simulation.

For control education, experiments have an immeasurable but profound impact. A student who sees an operating control system is awed by the system's magical ability to regulate itself. The visual aspect of control systems, lacking in traditional theory courses, can be one of the strongest selling points of our field.

While this section is the first in *IEEE Control Systems Magazine* devoted to experiments for control research, we look forward to future special sections on experimental aspects of control and their impact on both research and education.

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