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Theory vs. Practice: The Challenges From Industry

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Abstract: **This is a summary of presentations for the Theory vs. Practice Forum at the 2004 American Control Conference. It presents an industrial view of the gap between theory and practice, and initiates a dialog to: 1) address the gap from practitioners' perspectives; 2) help academic researchers better understand the issues in engineering practice and make their research more relevant; and 3) help practitioners gain a perspective of the potential impact of system and control theory to practice. Suggestions for the next steps in bridging the theory-practice gap are given.**

I. Introduction

The gap between theory and practice has been an age-old topic discussed across the spectrum in academia and industry. A simple keyword search on internet yields hundred thousands of citations from nursing, to marketing, to foreign policies. The field of control research and practice is no exception.

The proportional-integral-derivative (PID) based control technology has been in existence for close to eighty years. N. Minorsky described it in 1922 [1]. In 1942 Ziegler and Nichols provided a set of tuning procedures that are still being taught today [2]. Various control forms and tuning methods related to PID have continued to appear in literature. PID is still the tool of choice in over ninety percent of current industrial control applications [3].

Classical control theory, particularly the frequency response method, helps control engineers gain helpful insight on how and why the feedback control system works, as well as how to improve it. Modern control theory, from Kalman Filters to H_∞ control, represents the tremendous progress made in the last 40 years in mathematical control theory. But, the level of mathematics that is required to understand it, the assumptions of linearity and time invariance, and its dependency on the mathematical model of physical plants are some of factors that limited its appeal to practitioners.

The gap between theory and practice has been discussed for many years; see, for example, the special issue of the Control System Magazine [4] on this very topic. The discussions, however, have addressed the issue in terms of how the researchers in academia go about bridging the gap. But perhaps, the practitioners are just as responsible and interested, if not more so, in bridging the gap. As noted by Bernstein [5], "... there is a corresponding burden on control practitioners to articulate their needs and provide guidance and feedback to the research community." The Theory vs. Practice Forum at the 2004 American Control Conference (ACC) was designed to facilitate just that.

A. Meeting of the Minds

Generally speaking, control practitioners, such as those represented by ISA (the Instrument, Systems, and Automation Society – formerly the Instrument Society of America), the largest group of instrument and control engineers in the world, have not been up-to-date on the latest developments in modern control theory. Although the industry as a whole is motivated to reach out to academia and tap into this enormous pool of brain power, the task proves to be a very challenging one. Perhaps one reason is that the publications from basic control research in academia have all but become unreadable to an average control engineer. This makes the crossover from industry to academia extremely difficult.

On the other hand, it is much more feasible for academic researchers to learn real-world problems and work them into their research to make resulting solutions more practical. While each researcher is free to do this on his or her own, the process will be expedited if researchers and practitioners work jointly to define/formulate important industrial problems, design requirements, and constraints. This is perhaps the most difficult phase in applied research, and this forum is a first step in this direction. A panel of leading experts with various backgrounds was assembled to provide a set of industry-wide challenges, and to help researchers understand some of the difficulties and constraints of control engineering practice and the limitations of existing theory. The panel includes seven speakers:

- John Bay (DARPA)
- Peter Schmidt (Rockwell Automation)
- Babatunde Ogunnaike (Univ. of Delaware)
- Dimitry Gorinevsky (Honeywell)
- Michael Dudzic (Dofasco)

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- Dawn Tilbury (Univ. of Michigan)
- Steve Fedigan (Texas Instruments)

The forum starts with opening remarks by John Bay, who speaks on the underlining issues that contributes to the existence of the theory-practice gap.

B. Opening Remarks

Theory vs. Practice: More Than Just Applied Research
By John Bay (DARPA)

These introductory comments provide perspectives on the role of the engineering researcher in different domains: academia, industry, and government. In the three domains, the procedures and practices for research can be widely divergent. In an attempt to find the root cause of these differences, we can adopt the control systems terminology and conjecture that it is the researcher's "cost function" that dictates the investigatory trajectory. However, it must be recognized that the three constituencies do not live in sandboxes, and to define a success criterion that is too myopic can result in the "theory vs. practice" conflict as the natural result of "waterfall" technology maturation. These remarks attempt to provide a sufficient introduction to the differing motivations of "theoreticians" and "practitioners" so that applied research can be appreciated with the respect it deserves.

Sweating the details:
The basic researchers will claim that the inherent novelty or performance in a design should suffice to justify an investment in it. The details are something to be worked out later. This is where I make my claim: in most cases, no, they cannot. The "details" are part of a chain of dependencies that influence any engineering design. Why do you think testing and validation consumes so much of the cost of complex system development? In avionics, that can often be 80% of the development costs, and there is precedent for even more. The reason for this is that after-the-fact changes have a way of propagating up through the design layers, sometimes becoming dominant factors. A good systems engineer knows that small features can drive large costs. Think of the details as being insignificant off-diagonal terms at the beginning of the project, which become closed-loop de-stabilizers toward the end.

I liken the situation to a concept in the embedded computing community called platform-based design. In platform-based design, the characteristics and features of the execution platform (i.e., the processor, the RTOS, etc.) are explicit drivers of the software architecture and algorithms. It is not considered an unnatural procedure to start with the implementation platform and ensure that the concept fits the product. This approach is sometimes considered at odds with model-based design, in which the problem and its (software-based) solution are modeled in a formal mathematical way, and the development tools and techniques are all tailored to reference that common model. The control systems field is heavily model-based. A *good* model, though, should embody some understanding of the platform, or else, as we have seen in countless cases, we have an unrealizable solution.

Performance Measures:
It is clear to me now that in control systems class we have always been myopic, putting too much emphasis on computing numerical feedback gains and too little emphasis on the problem of deciding what we want to see, i.e., the performance criterion itself. This is often a very difficult task. Most optimal control books give lip service to the rationale for quadratic optimization criteria, and the older ones discuss things like ITAE, but real control systems—and real life—are more complicated than that. On some mornings, I know exactly what I want to happen during the course of the day. On others, I hope that things "just work out well" (i.e., applying minimax to the probability of a bad day).

Sometimes, the performance criterion is hard to determine. Control theory is being applied in new domains and in innovative ways, to plants that are not well described as transfer functions or state equations, and the old way of thinking about performance criteria needs to be revisited. We have changed our views on control performance several times in the last few decades (phase/gain margins, % overshoot, minimax, norms, etc.), and there is no reason we should stop now. I can think of several control applications where it seems that defining performance is the hardest issue. In large mixed-traffic networks, how are multiple, conflicting quality-of-service criteria best weighed against one another? In machine learning and intelligent control, aren't we handicapping the algorithm by fixating on simple, sometimes purely anthropomorphic cost or fitness functions? Why should those ubiquitous Q and R matrices in the quadratic regulator problem be as arbitrary as we treat them, and how do we always seem to get away with that?

I am reminded of the field of inverse optimal control, wherein a stable closed-loop system is observed and the cost function thereby extracted. This seems to get into the motivation of the control system: what does it really want? How does it become a success? What gives it useful skills? I first encountered these problems in the study of biomechanics where it was assumed that the human body's neuromusculoskeletal system must be optimizing something and discovering that something was the key to designing a good prosthesis. More relevant to my current interests, this theory has been used to model the behavior of adversaries, in a sense as a way to predict their intent.

Clearly, important problems can be solved if we understand the intent of our adversaries, assuming they are rational.

John Bay's opening remarks (see [7] for more details) are followed by six panelists. Each presents an industry-wide challenge and its possible tie-in to academic research.

II. A GLIMPSE OF REAL WORLD PROBLEMS

Control is a unique specialty that permeates all engineering disciplines, including electrical, mechanical, chemical, civil, and aerospace engineering. As opposed to narrowly-defined forms in textbooks, control-related problems come in all shapes and forms in practice. With limited time, the presentations show examples in just three areas:

1. Control problems in manufacturing industries
2. Health management in aerospace vehicle and steel industries
3. Control logic and algorithm implementations

In each example, industry necessities and the research needed to address them are identified.

A. Control problems in manufacturing industries

There are two problems presented in this section. One is a typical industrial control problem where a process variable is measured and regulated. First, through this problem, Peter Schmidt illustrates why a simple PI controller is still dominant in industrial control and automation, a billion dollar industry. He further explains the constraints as well as the motivation for new technology development in this industry.

Then, Babatunde Ogunnaike introduces an entirely new control problem. Instead of controlling the process variables in the manufacturing process, the new problem is defined as one of controlling the characteristics of the end product it produces.

Motion/Drive control in web industry
By Peter Schmidt (Rockwell Automation)

Manufacturing industries are typically slow to pick up on advances in new control theories developed either by academia or in-house. Major changes in existing products or new products are costly not only in development time, but also in marketing, testing, qualification, and training. Incremental changes are easier to implement and are more readily accepted by customers. In order to reduce the latency between the development of an algorithm by academia and the implementation by industry, engineers from both sectors must work together from the start. Understanding of the real problems and issues will aid in the successful transferring of new technologies. Many times we have a solution looking for a problem. This section address a few of these issues as they relate to motor/drive control as applied to the web industry.

Rockwell Automation deals with a variety of industries that utilize both motor drives and motion controllers. Drives typically control velocity and torque loops where motion control closes the position loop. Isolated motors, drives, and controllers are conventionally modeled and controlled. However, the customer and drive manufacturer must work together to develop the necessary control strategies when the motor is connected to a complicated load or process.

For example, tension T_1, is measured between two contact points along a web line (see Figure 1) and is a complex function of other tensions, roll velocities, and material properties. Many of these parameters are nonlinear, time-varying quantities. It is not always possible to know or measure the necessary values to calculate tension.

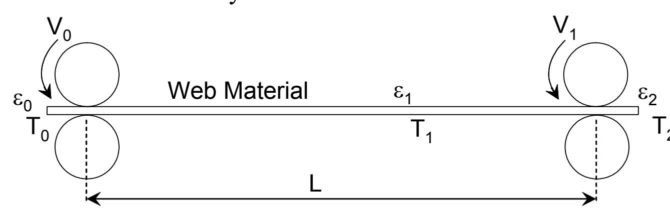

Figure 1 Single Web Section

Although there have been many different solutions developed to solve the tension control problem, some more elegant than others, they have not all been implemented by drive manufacturers. One reason is that simple PI torque or draw control loops work well enough. When "classical" techniques work, it is difficult to justify replacing them with "modern" control laws. In many cases the new algorithm can be shown to be mathematically equivalent to the old control equation. The value added to the controller must be clearly defined. Second, industrial control devices may not include the necessary tools to implement the new control algorithm. It is difficult to program a complex fuzzy logic or neural network controller in a drive that is programmed in assembly. Third, some solutions require special signals to be injected into the commands or specific trajectories to be followed in order to identify parameters or structures in the system. In many cases this is not acceptable to the customer because of the damage that would result to their machine or equipment. Finally, customers cannot afford or want to spend a large amount of time setting up or tuning a controller. The control/drive should work coming out of the box with a minimum amount of tuning. Industry is slow to replace a solution that works 90-95% of the time. In general, there has to be an order of magnitude improvement in some area before it is considered for replacement.

Industry is always interested in solutions that provide lower cost and non-invasive techniques to solve a control problem. This would also benefit the customer because it could increase process performance and product quality. However, the new solutions often require additional sensors, processing power, specially designed signals that may be difficult to generate, and more training.

Although most industrial control engineers understand modern control theory, classical techniques have been around longer and are easier to implement in many cases. In order to bridge the gap successfully, both sides must reach out and embrace the problem simultaneously.

Product end-use characteristics control for reactive extrusion processes

By Babatunde Ogunnaike (Univ. of Delaware)

Extruders belong to an important class of equipment used extensively in the polymer processing industry. Many polymer products are sold commercially in the form of pellets that have been blended and compounded in extruders to achieve desired characteristics. Reactive extrusion specifically refers to the special case where chemical reactions are *deliberately* carried out in conjunction with continuous extrusion. By thus combining reaction and extrusion in a single piece of equipment, reactive extrusion has revolutionized polymer processing, dramatically extending the range of achievable modifications of polymeric material characteristics.

The various advantages and disadvantages accruing from using the extruder as a reactor are fairly well-known and have been discussed extensively, in addition to issues relating to chemistry, reaction engineering, and general process design and operation. The key disadvantages of short residence time and poor heat transfer combine with the intrinsic complexities of the process to present major challenges for effective control of product properties. This is particularly important for the extruded and molded plastics sector of the chemical industry where the value chain extends from the monomer manufacturer through the polymer resin manufacturer to the resin processors (where extruders are used), on to injection molders and finally to the final end-user.

The traditional strategy of controlling only process variables on-line while depending on infrequent quality control lab sampling for ensuring adequate product quality has proved ineffective especially for the processes along this particular value chain.

To derive the fullest advantage from reactive extrusion in particular, it has become important:

1) To develop a paradigm for effective control of not just the process variables (Melt pressure, Barrel temperature, screw speed, etc.) or even the product properties (Melt index, viscosity, density, etc.) but also end-use physical characteristics (toughness, UV/Chemical Resistance, etc.) *to guarantee acceptable end-use product performance*.
2) Furthermore, effectiveness of the developed strategies will be enhanced by the development of *novel sensors* that can produce measurements of end-use physical characteristics as frequently as on the order of minutes, as opposed to hourly or daily lab characterizations.

The ultimate objective is to develop a framework for controlling end-use product characteristics and assuring acceptable end-use performance, thereby reducing waste and energy consumption.

The following is a summary of the key characteristics of this problem; they will influence the problem formulation and solution.

1. The available data and information are *heterogeneous* in the sense that process data are real-valued measurements available on the order of minutes; direct product quality measurements, when available at all, are available on the order of hours; end-use physical characteristics (stiffness/strength; modulus; UV/Chemical Resistance, etc.) are available perhaps once a day; finally, product performance in end-use (manufactured part acceptability) occur in the form of binary data (acceptable or *not* acceptable) and often on the order of weeks.

2. Effective strategies will involve models across the entire value chain, ranging from chemical process models to empirical correlations between quality variables and end-use characteristics to "Logistic" models to predict acceptability (a binary variable) on the basis of values of the continuous (i.e. real valued, as opposed to binary) end-use characteristics measurements.

The readers are referred to [8] for more detail on this and previous work.

B. Health management in aerospace vehicles and steel industries

Because the failures of a control system often lead to catastrophic consequences, health management has increasingly become an integral part of control design. First, Dimitry Gorinevsky addresses the problem in the context of aerospace vehicles, and then Michael Dudzic sheds light on abnormal situation management in steel industry.

Vehicle health management
By Dimitry Gorinevsky (Honeywell)

Vehicle health management (VHM) is an area of engineering activity that is currently experiencing rapid growth. Development of automated VHM systems is closely related to engineering of control and industrial automation systems and requires many of the same skills. Thus, the topic is of interest to the control systems community. An essential part of VHM is estimating the system health state from sensors and other data in the vehicle avionics system. Several types of important problems are encountered in the VHM systems engineering. These include diagnostics and prognostics for subsystems, as well as central VHM systems, integrating information for a large number of subsystems.

Motivation: Aerospace and advanced military ground vehicles are safety- and mission-critical systems with many limited-life components. Maintenance and support might make up to 95% of economic activity associated with operating the vehicle. Avionics (or vetronics) systems on modern vehicles host the control system, other information systems, and dedicated health monitoring sensors. Using the sensor data for automating maintenance events and increasing operational safety is an area of major up-and-coming systems development effort in industry. This includes such high-profile development programs as DoD Joint Strike Fighter, DARPA Future Combat Systems, and NASA Orbital Space Plane. In the future, most aerospace vehicles in commercial aviation, space, and military, as well as some advanced ground vehicles will have integrated VHM. Functionality of VHM systems includes diagnostics (determining health state, faults, and required maintenance action of the vehicle) and prognostics (predicting future evolution of the health management and incipient faults). Prognostics enable condition-based maintenance that can be performed just prior to the impending failure. An essential part of VHM is estimating a health state of the vehicle based on the sensor and other data available in the vehicle avionics system. Developing algorithms and systems for VHM requires much of the same skills as control systems engineering, e.g., algorithms for estimation, prediction, planning and scheduling.

Diagnostics: Diagnostics for maintenance automation can be performed off-line. Diagnostics functionality is also needed on-line, for system safety, control reconfiguration, and operator alerting. Most embedded controllers have Built-In Test (BIT) functions for detecting critical system failures. In the safety conscious aerospace industry, the BIT (and fault accommodation) functions might take up to 85% of embedded controller code, compared to the 15% for the main control algorithms. BIT functions are a part of controller development and use simple and reliable range check algorithms for the sensor data or internal variables indicative of system malfunction. Advanced estimation or detection algorithms are rarely used in industrial BIT design. Some of the representative uses of BIT are in turbomachines and in electrical power systems.

Development of BIT logic is highly dependent on application domain knowledge. In a large commercial aircraft, there might be about 3000 subsystems each served by an embedded processor hosting the control and BIT logic. The subsystem diagnostics logic is usually designed by a subsystem manufacturer possessing the needed domain knowledge. The distributed subsystems diagnostics would work with a central VHM system. A prominent example is the Central Maintenance Computer (CMC) developed by Honeywell for Boeing 777. The CMC receives BIT messages from the vehicle subsystems and identifies the fault based on this data. A single sensor failure might cause faulty operation and fault messages from 300 subsystems. By using a cause-effect and topological connection model, the CMC could trace the messages back to a single root cause.

Prognostics: In the existing systems, prognostics necessary for the predictive maintenance are achieved by trending parameters indicative of the system health from one usage cycle to another (typically flight to flight). A case study and advanced algorithms for predictive trending are discussed in more detail in an accompanying ACC 2004 paper by the author. The prognostics trending includes several stages of the data processing. First the data is collected and stored during each aircraft flight. After each flight the collected data is then transferred into a ground server and processed. By using a detailed model of the nominal system behavior, model prediction residuals are then formed. Ideally, these residuals are zero if the system is healthy and nonzero in the presence of the faults. By using fault signature models, the fault intensities (degree of performance deterioration) can then be estimated from the residuals. The estimates of the performance deterioration parameters can be combined with the models of deterioration to yield the estimated trends for the faults. There is one seemingly fundamental issue when designing prognostics trending systems. In many cases, accurate models of the nominal system behavior can be available. Such models are routinely built and verified against experimental data in the course of an aerospace system development. It is more difficult to obtain accurate models for the various fault modes encountered in the system operation. For one thing, some of the failure models might be not even recognized until the system is deployed and operational experience gained. Another issue is that little data might be collected for a fault condition, since it is not easily reproducible in a controlled experiment.

Theory vs. practice in health estimation: In the controls community, extensive literature on fault estimation and detection exists. The faults are modeled as either unknown parameters or unknown disturbance signals. Most of the theoretical literature concerns fault estimation in linear dynamical models. These estimation approaches are rarely used in practice for VHM system design. In practice, most models that might be used for diagnostics or estimation are nonlinear. Often these might be detailed simulation models containing empirical nonlinear maps that are put together by domain experts. They can be best used as black box prediction models. As described above, the main emphasis in practice is on simple BIT/BITE algorithms for vehicle subsystems, central VHM systems, and prognostics algorithm development.

Industrial need: The most important industry need in the VHM area that should be satisfied by academia is in preparing engineers who are well-trained and capable of diagnostics and VHM system development. There is some need in the area of new advanced methods/approaches for estimation, diagnostics, and prognostics. Much of the available work in the VHM area would likely involve more basic estimation and diagnostics algorithms by using standard models and processes. There is a strong need in the modeling and simulation skills including integration and validation of consistent modes from diverse interdisciplinary data. Fault modeling remains a big issue because of the scarcity of the information and data. Some of the existing data-driven modeling and identification methods might be applicable.

Abnormal situation management in steel industry

By Michael Dudzic (Dofasco Inc.)

This section deals with on-line industrial applications in the area of process monitoring and fault diagnosis (i.e. Abnormal Situation Management) through the technology of multivariate statistics (MVS). At a steel continuous-casting facility, an on-line MVS monitoring application was developed that combines both continuous and batch MVS technologies into an integrated monitoring solution. Continuous MVS-based monitoring is used for continuous, run-time casting operation. Batch MVS-based monitoring is applied during the start-up operation while the process is in the transition to the run-time operation.

This example demonstrates how technology was taken from academic theory to on-line implementation. Findings from the development and implementation of this and other MVS-based applications will include the following:

- Fault detection needs and expectations in industry
- Issues and conflicting objectives between academics and industry
- Necessities for successfully implementing Abnormal Situation Management technology solutions in industry
- Application methodology that meets the needs of both academics and industry

C. Control logic and algorithm implementations

For many researchers, the implementation of control logic and algorithms is an afterthought, compared to the process of solving a problem mathematically. As pointed out earlier by Peter Schmidt, the difficulty of implementation plays a big part in determining if an advanced controller is applicable. In the following section, Dawn Tilbury makes observations on the existing practice of control logic design in the automotive industry using the predominant programmable logic controller (PLC) platform. She is followed by Steve Fedigan, who discusses the implementation of advanced control algorithms in modern digital signal processors (DSPs).

Logic control design in the automotive manufacturing industry

By Dawn Tilbury (Univ. of Michigan)

Many academic researchers have been working on the improvement of industrial logic design. The problem that many are trying to solve is the perceived inefficiency of the current methods, which use primitive, low-level design languages, practically no logic reuse, and are very time consuming. In searching for a solution, researchers have focused on methods that can be verified against a known specification language, or that can be automatically generated from a specification. This work has generally been done with a minimal understanding of the actual current logic design methods.

In this work, the results of an observational study of the current methods of creating control logic are presented. The current specifications are generally informal and loosely defined, and the typical logic designer is responsible for determining the details of system behavior, anticipating potential problems, and coordinating with other designers. This is a larger range of problems than generally addressed by logic design schemes focused on verification or automatic logic generation.

Logic Designers: One of the most striking observations is the expertise of the logic designers, especially the team leaders. The designers are capable of understanding and debugging wiring diagrams; they understand both the machine and the machine users, and often imagine many possible safety issues which would otherwise go unchecked.

The logic designers attempt to consider every possible condition that could occur as they create the control logic. Among the errors and special conditions that they actively considered were:

- Intentional circumvention of the built-in safety devices
- System-wide power loss at any time
- Processor failure and replacement (the new processor should correctly handle all parts in process, with minimal part loss)
- Users manually altering the contents of the memory
- Relay failures
- Sensor failures
- Tool breakage

The goal of the logic was to operate the machine as safely and productively as possible under any conceivable condition.

Ladders and their development environments: The choice of control hardware, development language and development environment are extremely coupled. For example, if an end-user requests that Allen-Bradley control hardware be used, it implies that the project will be developed in ladder logic using Allen-Bradley's RSLogix software. Control vendors are experts in creating a unified control package, but not in creating a usable development environment. This likely adds to the difficulty of using the various development environments.

New logic is typically developed from timing bar charts, which describe the time dependent (sequential) behavior of either the physical machine or the communication signals needed. This is translated in an ad-hoc manner into time-independent (declarative) logic. This mapping is neither consistent from one timing bar chart to another, nor easy to determine for a given timing bar chart.

Despite some of the apparent disadvantages described in this paper and others from academia, ladder diagrams have some advantages. For example, it is nearly impossible to create an infinite recursive/iterative loop using ladder diagrams, especially using the methods described here. This means that even if a portion of the logic is poorly written, most of the machine will continue to operate as designed, including safety interlocks. In addition, the primary users of the control logic began their careers as electricians, and the framework of ladder diagrams provides a clear and consistent model of the operations of a complicated computer, without requiring programming. A final point: PLCs do not crash. Designers routinely talk about machines running for years without problems. A machine will probably need to be stopped due to an error in the logic, or an error in the machine, but they almost never stop due to an error in the underlying operating system of the PLC. Any proposal to replace ladder diagrams must preserve as many of these advantages as possible.

The readers are referred to [9] for more details on this work.

Implementation of advanced algorithms in modern DSP chips

By Steve Fedigan (Texas Instruments)

In recent years, advances in DSP hardware have given designers the ability to experiment with complicated control schemes on an increasingly broad range of systems. This talk will address implementation issues in digital filters and state-space controllers, which are at the heart of most modern control systems. We start off by investigating the tradeoffs between different state-space forms and filter realizations. Following this, we look at techniques for addressing problems typically encountered in fixed-point implementations.

Specifically, we examine how dithering methods can be used to reduce truncation error and how scaling techniques can be successfully applied to prevent overflow and improve numerical resolution. After covering fixed-point issues, we discuss how special features of DSP hardware such as multiply-and-accumulate units, parallelism, and circular addressing modes can be employed to execute control computations more efficiently. The next part of the talk focuses on two successful design examples: a feedback-controlled subwoofer and a sensorless switched reluctance motor drive, which illustrate the DSP's role in reducing overall cost and improving system performance.

Early embedded control systems were implemented on single board computers using 8-bit micro-processors. While these devices were reliable work-horses, their lack of computational power frequently required hand-coded assembly even to execute digital PID controllers. Further advances led to microcontrollers, which have a variety of on-chip peripherals such as A/D converters and counter/timers but still had limited computational abilities. These micros were followed by DSPs which can execute high-order digital filter structures in real-time. This talk examines a MIMO state-space controller, which is at the heart of so many modern control methods, and looks at ways we can employ the special features (multiply-and-accumulate unit, circular addressing mode, etc.) of the DSP to execute it efficiently.

After this, we turn our attention to two sample applications which demonstrate the DSP's ability to reduce cost and enhance system performance. The first application we consider is a sensorless switched reluctance motor (SRM) drive system. SRMs are brushless motors; and therefore, must be commutated electronically. While brushless operation has important reliability advantages, discrete position sensors are typically mounted on the shaft to indicate when commutation should take place. Since this adds cost and offsets reliability gains, there has been a great deal of interest in eliminating these position sensors. In this sensorless system, the DSP uses electrical signals in the active phase winding to estimate shaft position and make commutation decisions. This position estimator must be accurate to ensure efficient torque production and must operate reliably in the presence of noisy voltage and current measurements. Besides executing commutation decisions, the DSP uses the same signals to estimate and control shaft velocity. Results have been encouraging: sensorless startup under full torque is reliable and accurate velocity control has been achieved between 150 and 6000 RPM.

The second control application is a highly efficient DSP-controlled subwoofer. In this system, a commercial subwoofer's efficiency is enhanced by replacing conventional ceramic with rare earth magnets and by reducing voice coil resistance to a fraction of an ohm. While these changes can increase efficiency by 8x, they distort the speaker's bass response by increasing damping at the speaker's mechanical resonance. To obtain a more desirable sound pressure level (SPL) curve between 20 and 200 Hz, an adaptive DSP-based compensator is used to provide positive velocity feedback based on voltage and current in the coil windings. This solution performs better than open-loop equalization techniques since it can adapt to changing parameters such as variations in DC resistance.

III. The Next Step

Collectively, the seven panelists at the forum provide researchers with a practitioners' view of the theory vs. practice issues. In particular, the following observations are made:

- Applied research should be encouraged and respected in academia.
- Details such as real world constraints need to be incorporated into research.
- Performance criterion should be made consistent with the practitioners' rationale.
- Industrial processes are complicated, but a premium is put on the simplicity of control algorithms.
- Advanced control algorithms need to be made transparent to engineers and show clear cost-benefits advantage.
- There are new forms of control problems in industry, such as the one of controlling the product end-use characteristics. Both sensor and control designs need to be revisited.
- Health management and abnormal situation management are integral parts of control systems and are becoming increasingly important.
- The theory/method based on linear models is ill-suited to systems and problems in practice that are predominantly nonlinear.
- Some industrial practice, such as the control logic design in a PLC, may look primitive to researchers, but there are reasons for its survival; understanding these reasons could help researchers better comprehend industrial design constraints.
- Today's DSP chips are quite capable of implementing complex algorithms, but there are many details that need to be included in research.

While it is an important step, the forum only begins to scratch the surface of the theory-practice gap. As researchers get a good view of industrial problems, the next step is perhaps to redefine, or reformulate, the research problems with realistic assumptions, and explore alternative design paradigms. In the following, we use a typical motion control problem as an example.

Think out of the box (1): The Newtonian law of motion for an electromechanical system can be seen as

$$m\,\ddot{y}(t) = f(t, y(t), \dot{y}(t), w(t)) + u(t) \qquad (1)$$

where y(t) is position that is measured and to be controlled, *m* is the mass, u(t) is the force generated by a motor, and w(t) represents the external disturbance such as vibrations and torque disturbances. The friction, the effect of inertia and various other nonlinearities in a motion system are all represented by the function $f(t, y(t), \dot{y}(t), w(t))$, which is generally nonlinear and time-varying. The problem here is to design a feedback control law such that *y(t)* follows a predetermined reference signal, r(t), within a given accuracy requirement.

To solve the position control problem using existing control theory requires an explicit description of $f(t, y(t), \dot{y}(t), w(t))$. The process of obtaining this function is a main part of modeling. The dependence of control theory on such a model has been attributed by some [4-6] as a main culprit of the theory-practice gap. But, must we have an explicit model in order to control the device?

Let's consider the case where y(t), $\dot{y}(t)$, and $\ddot{y}(t)$ are all physically measured, *m* is known, and the controller is implemented digitally with u(t) as its output and t_s as the sampling period. Then $f(t, y(t), \dot{y}(t), w(t)) = m\,\ddot{y}(t) - u(t)$ can be obtained at every sampling instant, $t=kt_s$ $k=1,2,\ldots,$ and the control law, at $t=(k+1)t_s$,

$$u(t) = -f(t, y(t), \dot{y}(t), w(t)) + u_0(t) \qquad (2)$$

reduces the plant in (1), approximately, to a simple double-integral plant

$$m\ddot{y}(t) = u_0(t) \qquad (3)$$

This begs the question: what do we really need to know to be able to control something? A detailed, explicit, accurate mathematical model gives us complete and global knowledge of the plant. However, information obtained through sensors, or for that matter, observers, maybe viewed as "local" information, at a given time, pertaining to a particular operating point. The above example seems to suggest that the partial and local information of the plant maybe sufficient for control purposes.

Interested readers are referred to [5,6,10-12] Note that in the context of control law (2), an extended state observer for (1) is proposed in [13], which estimates $\dot{y}(t)$ and $f(t, y(t), \dot{y}(t), w(t))$ with y(t) as the only measurement available. Practical implementation and tuning of the controllers developed in this framework are discussed in [14].

Think out of the box (2): Balance sufficiency with perfection. If a controller action is only 80% right, it is only 20% wrong. If at each control update, as the process response develops, the controller corrects the residual 20% incorrectness, then after N updates, the net influence is $(1-0.2^N)*100$ percent correct. Do we need it to be any better?

Reformulation of Control Problems: In the process of taking concrete steps in bridging the gap, the control problem formulation needs to be carefully examined. Assumptions proceeding theoretical developments should be constructed so that they are realistic. The design criterion should be consistent with the performance measures in an actual application, instead of one selected merely for the convenience of finding a mathematical solution. Controller structure and controller tuning should be transparent (insightful) to engineers who can easily make adjustments on the factory floor.

The difficulty and importance of such problem reformulation can be easily underestimated. The practitioners and researchers must work together to come up with formulations that are not only full of practical insight; but also fit certain theoretical framework, where rigorous research can be conducted. The underlining causes examined by the speakers of this forum and other researchers can certainly be used as a guideline in this effort. Practitioners play an important role in articulating the industry needs, perhaps at an abstract level, to researchers. They can also help researchers identify research directions that more likely lead to practical solutions. On the other hand, for the researchers from academia determined to make their research relevant to engineering practice, they need to listen to practitioners carefully in order to understand the practical constraints. At the same time, they have to see though the nuts and bolts, and find the underlining basic research questions.

IV. CONCLUDING REMARKS

The gap between theory and practice has been discussed by the control research community for some time now. It's time to do something about it. This special session at 2004 ACC is a first step in this direction. We hope that sessions like this will be regularly held at ACC and other conferences in the future to help create a continuous dialog among researchers and practitioners.

The emphasis of this session is to show a wide range of industry problems to researchers in academia. As we make progress in this effort, a future session could be held, perhaps in the next year's ACC, for the practitioners and researchers to jointly articulate practical control problems and create a theoretical framework where assumptions and constraints are consistent with real-world problems. It is our hope that such new problem formulations will lead researchers to solutions that start to narrow the gap between theory and practice.

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