Controlled Computations or Computer Control?

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Background Statements

I will start this position paper with some statements regarding facts that, during the last 10 years, in my opinion, have dramatically changed the environment in which a control engineer—or, more generally, a systems engineer—must operate.

- The complexity of (control) systems has increased dramatically. This is manifested, for example, in tighter engineering specifications, the need for adaptation, requirements for multisensor integration, the need to account for contingencies (multiple modalities), totally digital implementations, and the need for a mix of numerical and logical computations. As a result, control systems design must now be viewed as an interacting part of integrated design.

- Advances in computer technology, both in hardware [very large scale integration (VLSI), large memories, artificial intelligence (AI) chip, distributed, parallel machines] and software [AI, symbolic algebra, computer-aided engineering (CAE)], have not been properly understood by control system theorists and designers. (I would even say there is an awareness problem here.) There is, at present, a growing gap between the sophistication and power of this technology versus its use in control systems synthesis. In addition, the needs of control systems have not been properly embedded in microelectronic chip design.

- Computers of all kinds have become indispensable tools, both as design aids and as elements of the solution (i.e., the implementation of a control algorithm, design, or scheme). As a matter of fact, the design of computers and computations (and their formal counterparts) look more and more similar to the design of present-day control and communication systems (a phenomenon that is not unexpected).

It is relatively easy to cite specific examples from many areas of engineering and science where the preceding facts manifest themselves in a very profound way. I will use a few just for illustration purposes:

- How do we control systems characterized by complex—often, poorly defined—models? Typical examples include chemical process control, where, often, it is difficult to design "correct" loops and equations.

- How should one automate the operation of systems defined by precise, highly complex simulation models? Problems in flexible manufacturing systems represent generic examples, wherein time-precedence constraints and the need for adaptive automation further complicate design.

- How should we design systems controlled by asynchronously operating, distributed, communicating controllers? Examples include the computer-aided design (CAD) of computer/communications networks, dynamic capacity allocation in communication satellites, and efficient management of mixed traffic (voice, video, data).

- How can we develop design tools for real-time, high-performance, non-Gaussian signal processors? Examples from radar, sonar, image, and speech signal processing abound.

- How can one integrate multiple sensors for robust, digital, feedback control of nonlinear systems? Examples include many-degrees-of-freedom robotic manipulators with vision, force, and pressure sensors, as well as advanced aircraft flight controllers especially designed for the new generation of unstable aircraft.

Two Questions

Having made these statements, let me pose and examine the following questions:

- Are these developments in computer technology (both hardware and software) enhancing the future of the field of control system engineering, or systems engineering in general?

- Can we identify a basic reason for the gaps mentioned and a course of action that can

open new opportunities for progress and advancement in the field?

It is true that our field is a relatively new one. It has made, however, substantial contributions to engineering, science, economics, and also the standard of living in the United States and other countries. It is my opinion that the current state of the field is an excellent one. The advances in computer technologies provide the opportunity for vigorous and synergistic development of balanced new theories that combine powerful analytical tools with these technologies to produce better performing systems. So, my answer to the first question is unequivocally yes. Now, whether the research programs at major universities and, perhaps more importantly, the funding programs at various public agencies and private-sector sources are addressing these issues is a totally different matter. This is where I believe some drastic changes are necessary.

Regarding the second question, the answer (if you think about it hard for some time) is relatively straightforward. Control systems, in general, are man-made devices that collect data from a physical system, interpret them, and produce control signals. In this process, it is very important to pay attention not only to the analytical development of the relationship between control actions and observables but also to the models of *both* the physical system (to be controlled) as well as the man-made system (the controller). Of course, today both can be man-made. Where I believe attention has been lacking in the last 10 years or so is in training, educating, and doing research on the empirical component of our science, the one that naturally addresses these very important modeling questions. Control and systems engineering depend *critically* on models. This lack of emphasis on modeling has not allowed us to link early with new models of computers, or VLSI devices, or even new models of computation. This has led to total neglect of the implementation question.

To summarize this point and to answer the second question, let me just state that, unfortunately, currently available theories and design methodologies for control systems are not in synchrony with the currently available

or planned implementation media, be it special-purpose chips or computers with specialized architectures and capabilities. More precisely, the available design theories and performance evaluation methods were developed for different (now often obsolete) implementation media, such as analog circuits and sequential machines. I furthermore claim that, although for some problems—admittedly a small class—it is feasible to develop improved designs using the new hardware capabilities and existing theory, in the majority of problems, there is a substantial lag between the available hardware potential and its realization in the systems being built. In my opinion, we can no longer separate the design of a system from the implementation problem.

Related to the issue of modeling is the broader problem of design integration. Emphasis on modeling (in the sense described earlier) mandates emphasis on models of actuators and sensors, a technology strongly linked with computer technology. Sensor and actuator technology is currently undergoing dramatic changes, and more revolutionary developments are expected in the next decade. Control systems design must now become a well-integrated part of the overall design, with strong links to other engineering and scientific disciplines involved; in other words, design for control is now a reality.

Computers and Control Systems

To proceed further with the analysis of the relationship between computers and control systems, I would like to emphasize again that as the years go by, they look more alike, and the tremendous opportunities that open before us may be lost if we do not pay attention to computers and computation models. As a matter of fact, this interaction between theory, design, and implementation manifests itself in many unsuspected ways. For example, certain optimization-based design algorithms work only because of the human interaction via graphics (an implementation of an algorithm question).

A point that should be emphasized here is that paying more attention to properly modeling the system and the controller often requires more sophisticated and new analytical and computational tools. For example, it appears that although we are convinced that non-Gaussian real-time estimation problems require massively parallel computations, the signal and observations models we use in control systems have not been selected on the basis of their ability to induce parallel computer implementations. New models are

needed. Similar results abound when one starts investigating distributed, asynchronous algorithms. As a matter of fact, I believe that new mathematical, analytical, and computational advances are needed to take full advantage of the new technologies. On the other hand, a tremendous, albeit critical, opportunity exists for system scientists and engineers to influence the chips and computers designed and built by the microelectronics industry.

Research Emphasis

I will close this short position paper with some suggestions of where research should be emphasized in order to capitalize the full development potential of our field. I will categorize these areas by the technical (key) words provided by the editors.

Computer-Aided Engineering

Research is needed badly to investigate the effects of interactive graphics, interfaces, etc., in the design of sophisticated CAD systems. Further research is necessary in order to properly understand the changes needed due to the forthcoming integration of symbolic and numerical computation, which changes the type and form of the "knowledge base" used for design.

System-Level Design Tools

What we really need is research for the development of design tools that can handle integrated design from conception to implementation. Systems engineers today are called upon to solve complex control and communication design problems for systems often described by huge simulation models. To ask a systems engineer to solve the complex design problems of today without such a combined arsenal of tools is similar to asking a VLSI chip designer to design the chip without the expert CAD tools now available. In this context, I have found AI languages (LISP, PROLOG, MACSYMA, etc.) to offer a superior medium for design problem definition, conceptualization, and implementation. Serious research in new languages and new architectures is needed here, since these tools must be fairly flexible, descriptive, and fast.

Workstations

In my opinion, what is needed is a *system engineer's workstation*, which is really a design superworkstation combining an AI machine with a graphics engine and a multiprocessor "number cruncher." This superworkstation is part of a network of similar and other workstations and computers, so that the engineer can really have the capa-

bility to run several modules of the design software system on different machines concurrently. The AI workstation provides the direct interface with the user, the (often symbolic) problem description, and modeling. The multiprocessor "number cruncher" provides the necessary computing power for almost real-time execution. Finally, the graphics engine provides real-time graphics for simulation, testing, validation, and feedback to the designer.

Real-Time Implementation

This is a volatile issue, since the meaning of "real time" relates strongly to the available technologies. "Convolution" was not a real-time operation 10 years ago, but it is today. Furthermore, it is clear, at least for control and communication systems purposes, that the question is not how fast the chip is, but rather an architectural one. Therefore, research in distributed, asynchronous, and synchronous architectures, geared toward specific control problems, would be very beneficial.

AI Issues

One has to be extremely careful here. I am not in favor of heuristics-based expert systems. However, the development and theory of systems that can reason in a specified domain of control engineering seems to be rather feasible and attractive. For design systems, AI can be very helpful in providing easy model modification, model manipulation, handling the initial intuitive and empirical design steps, and reducing nuisance programming. Far more exciting are the possibilities offered by AI chips in the feedback loops of control systems.

VLSI and Architectural Issues

This is a totally implementation-related topic. It is clear, however, that deeper understanding of architectures for control and signal processing is needed for progress in some very demanding areas, such as multisensor feedback control of advanced robotic manipulators. In addition, the limitations of VLSI chips must be properly understood in relation to control systems design, and proper feedback should be provided to the manufacturers.

Finally, I would like to state that these technological advances offer the possibility of integrating design for many engineering automation and signal processing systems. I am confident that we will succeed in meeting the challenges described here and that we will prosper from the opportunities they imply.