Professor R. E. Kalman - Reflections on His Way of Thinking

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My Connection to Professor Kalman

- Undergraduate degree in EE from IIT Bombay in 1977
- Ph. D. student under Professor Kalman during 1978-81
- A personal essay in IEEE Control Systems Magazine, April 2017
- This talk: reflections on his unique scientific philosophy

System Theory and Mathematics

The terms "systems," "systems concepts," "systems approach," and "systems science" are used so widely and so broadly today that they tend to connote fuzzy thinking. For us, however, a *system,* or more correctly, a *dynamical system,* is a precise mathematical object; the study of system theory is then largely, although not entirely, a branch of mathematics.

— Page 1, Topics in Mathematical System Theory (TMST), Kalman, Falb, and Arbib.

System Theory and Mathematics

To put it more bluntly, *control theory does not deal with the real world, but only with mathematical models of certain aspects of the real world; therefore the tools as well as results of control theory are mathematical.*

— Page 27, TMST.

System Theory and Algebra

Although convergence conditions are essential to lend mathematical respectability to transform methods, in the engineering literature they are treated *very loosely and yet with apparent impunity.*

Why?

The reason is that, in the vast majority of applications to linear system theory, we may restrict our attention to finite-dimensional systems; then convergence plays no role whatever, since everything may be expressed in algebraic terms.

— Page 246, TMST.

Thoughts on Science and Technology

It is tempting to speculate about the implications of this result for problems in biology, especially the theory of the brain and in the higher animals. It could be true that it is hopeless to try to understand brain functions solely on the basis of anatomy (wiring diagrams). Perhaps the problem will become relatively transparent only after we have developed a theory (vaguely analogous to the present one) powerful enough to give us the main features of the anatomy.

— Page 66, TMST.

Intellectual Rigor in Scientific Thinking

In the nonadaptive control problem (when data on the plant structure are given) dynamical properties of the plant are assumed to be exactly known, and it remains "only" to determine the instantaneous state. This is relatively easy, for structural data represent a very large amount of information, stemming from centuries of work in physics and chemistry. A machine which could provide adaptive control for arbitrary plants could also replace human beings in scientific experimentation and model building. We regard adaptive control as a problem for the future and shall not discuss it further here.

— Page 51, TMST.

Physics and Control Technology

Indeed, in my opinion, the development of technology since Newton is an even greater human achievement than the development of physics, although it is important to remember that modern technology is dependent on prior knowledge in physics. And one of these great achievements concerns the problem and technology of control, which is also one of the most important system problems.

— Acceptance Speech, Kyoto Prize.

High Praise for Technology

Such technological achievements as manned flight, the transistor, computers, integrated circuits, the laser and many others might well be far more important to humanity as a whole than advances in the basic sciences, and they are largely system problems. The individuals who have contributed to them are not easily identifiable. But that should not diminish our thanks for the contributions involved.

— Acceptance Speech, Kyoto Prize.

Prejudice and Modeling in Social-Behavioral Sciences

A prejudice-free methodology of dealing with noisy data does not exist at present. Conventional ideas of statistics cannot lead us to it. Yet it is surely not impossible to find a way. It may take another Newton to accomplish the leap from exact (noise-free) realization theory to noisy realization theory. I am more modest in my hopes; I predict that someday someone will stand here to receive your very generous prize for it. He will surely have deserved it.

— Acceptance Speech, Kyoto Prize.

Beyond Science

Obviously there are things far beyond high technology, far above what we know about science today, things that are beyond anything our generation can analyze, think about, imagine, feel. I take as my last words the beginning of a medieval hymn which Mahler used to begin his Eighth Symphony,

Veni Creator spiritus.

("Oh come, Creator of the human soul.")

— Acceptance Speech, Kyoto Prize.

My Reflections: Questions for 2017 and Beyond

- Vision for Systems and Control
- Change of Paradigm
- Convergence and Multidisciplinary Research
- Technological Advances
- Research to Innovation

Vision for Systems and Control

The word "system" is one of the hundred most used words in the english language. Thus, it is only to be expected that many fields of engineering and sciences claim ownership of systems. Professor Kalman had a very sharp and narrow view of system theory ... Will this narrow and sharp definition serve the system and control theory community well in shaping the research agenda of the field in the coming decades? How should we frame an intellectually rigorous view of system theory that keeps our field exciting and at the forefront of scientific enterprise?

... it is crucially important to expand the scope of system theory research to include not only adjacent fields of engineering such as communications and networks but also systems oriented research subfields from computer science, physics, neuroscience, systems biology, social-behavioral sciences. ...

While there is a potential danger of loss of focus in such an expansive view, the ultimate benefits will be very significant. By adhering to strong traditions of intellectual rigor, the dangers can be minimized.

Change of Paradigm

Professor Kalman's early work created a new paradigm (in the sense of an "exemplar," as used by Kuhn,) shift in what constitutes research achievement and in writing of research papers. Rigorous theorem-proof mathematical style eliminated loose analysis and thinking. ...

However, there are at least two issues that require further thinking with changing times. One is the significant opportunity (and need) for empirical data and experimental investigations to influence the development of the field, the importance of questions being studied, and ultimate relevance and importance of the knowledge being generated. The other issue is the effective leveraging and synergistic integration of dramatic advances in computing, machine learning, data sciences into the system and control research agenda.

How should we reenvision the system and control research paradigm that is suitable for the current reality and the coming years? I believe that basic research in control theory falls squarely in the "Pasteur's Quadrant" ... Therefore, it is important to have robust connections between developments in control theory and challenging applications problems ... .

Convergence and Multidisciplinary Research

Societal grand challenges such as climate change, health, aging, energy, water, food, economic growth, etc. are not neatly formulated as questions within established disciplines. They often require strong collaborations across physical sciences, life sciences, social sciences, computing, engineering, and arts and humanities.

How would Professor Kalman approach such challenges? Would he agree with the claim that "convergence" represents a powerful new paradigm for research and knowledge creation? I believe that societal grand challenges offer a new opportunity for research and knowledge creation. ... New, valuable knowledge is and can be created through deep integration of knowledge bases, tools, techniques and modes of thinking from physical sciences, biological sciences, computing, engineering, and social-behavioral sciences in creative ways.

Resulting advances in knowledge do not fall easily in any one domain but are very valuable for societal progress. Control theory and engineering are ideally positioned to participate in such convergence style research.

Technological Advances

We have seen very large technological innovations in the last two decades that have had large societal impacts and promise to continue to do so. Internet, mobile phones, e-commerce, social networks, 3D printing, gene sequencing, and gene editing, to name just a few. Professor Kalman clearly admired technological advances. How would he advise the system and control theory community to engage with these and future technological innovations? I believe there is a very large opportunity for control systems researchers to participate in major technological advances underway.

Research to Innovation

Connecting research discoveries to innovations in products and processes has become a major driving force in contemporary engineering and science research. For example, the Innovation Corps program at the U.S. National Science Foundation is providing experiential education to researchers on converting research advances into real world innovations.

In retrospect, the Kalman filter and modern control became high impact innovations and were adopted in different industries. But much has changed since then.

How can the system and control theory research visions and paradigms integrate and leverage our increasing understanding of the nature of the innovation processes? I believe that control systems engineers are in a great position to build on their "systems" orientation and leverage ideas such as design thinking, lean startup, rapid iterations, etc. for successful engagement in innovation processes.