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Professor R.E. Kalman–Reflections on his way of thinking

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A R T I C L E I N F O

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A B S T R A C T

Professor R. E. Kalman passed away on July 2, 2016. His remarkable impact on the field of system and control theory and wider domains of science and engineering is now enshrined in text books, archival scientific and engineering literature, and numerous products and achievements of modern technology. In this paper, I will share some thoughts on his way of thinking about research, science, and engineering.

1. Introduction

Professor Kalman was the founder and visionary intellectual leader of the field of mathematical system theory. His contributions to optimal control, optimal estimation and filtering, realization theory, and mathematical system theory are at the foundations of these fields. They have significantly influenced much of the subsequent developments. Their influence transcends well beyond system and control into diverse fields of engineering, mathematics, physical sciences, social sciences, and others. Also, his contributions have been critical in enabling many products and achievements of modern technology. Since these are by now very well documented in text books and scientific literature, I have chosen to not focus on these aspects in this paper.

I was extremely fortunate to have been Professor Kalman's doctoral student from 1978 to 1981. This gave me an exceptional opportunity to learn from him in my formative years as an academic researcher and scholar. Beyond his very impressive talents for mathematics and engineering, he had a unique and particular scientific philosophy. It guided much of his work and his interactions with the research community. This very brief article is aimed at highlighting some aspects of how he thought about research, system and control theory, and the larger realms of science and engineering. It is also a complement to a more personal tribute (Khargonekar, 2017) to Professor Kalman.

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2. System theory and mathematics

Professor Kalman regarded much of his work as being mathematics. Indeed, for him system and control theory were simply a branch of mathematics. For example, consider the following paragraph:

> 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) by Kalman, Falb, and Arbib (1969).

> 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 (Kalman et al., 1969)

These statements have their roots in his early work on Kalman filtering and optimal control where he combined tools from linear algebra, differential equations and stochastic processes and made extremely creative and pioneering contributions. These groundbreaking achievements set the paradigm for research in system and control theory and laid the foundations for the newly developing field of mathematical system theory. Given this perspective, it is particularly interesting to observe that early applications in the space program facilitated by the arrival of digital computers certainly underscored the relevance and impact of his theoretical contributions.

The strong views expressed in the quotes above are, and must have been viewed in the1950's, a significant departure from the traditional view of control systems as an engineering field that draws from mathematics. In retrospect, it is clear that this view had remarkable influence on the actual conduct of research in control systems where rigorous theorem-proof style research papers became the dominant paradigm for what constituted research achievement. Later developments in the control systems field such as robust control and engineering applications of control theory can be seen as attempts to bridge the gap between mathematical theory and real-world applications.

Professor Kalman introduced advanced tools from ring theory, modules, and algebraic geometry to study problems such as the realization problem in linear system theory. This is the problem of finding the model of a dynamical system from input-output data. There is a telling quote that sheds some insight into his reasoning and approach that very strongly emphasized algebraic structures. He wrote:

> 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 (Kalman et al., 1969)

At a personal level, much of my early work in algebraic system theory, systems over rings, matrix fraction representations, invariant theoretic analysis of the linear-quadratic optimal control problem, and feedback control was deeply influenced by Professor Kalman's insights into the important role of commutative algebra and algebraic geometry in linear systems and control. For much of the1970's, he focused on creating a community of researchers that worked at the intersection of advanced algebra, algebraic geometry, invariant theory and mathematical system theory.

The fundamental structure of the linear-quadratic-Gaussian controller as the combination of the Kalman filter and optimal state feedback gain is one of the most important contributions made by Professor Kalman. I drew much inspiration from this foundational achievement in my own work in state-space $\mathcal{H}_\infty$ control theory.

3. Thoughts on science and technology

Professor Kalman had a wide range of intellectual interests ranging from mathematics to physics to neuroscience to economics to technology. He drew general inferences from the specific deep results in mathematical system theory. For example, in TMST, he wrote about the beautiful structure of the classic output feedback controller that combines the Kalman filter with the optimal state feedback gain. He then went on to speculate on what it might mean for the structure and the function of the brain:

> 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 (Kalman et al., 1969)

There has been dramatic progress and tremendous interest in all facets of neuroscience. I wonder how closely he followed, especially in his later years, the very interesting developments in neuroimaging, learning and memory, neural engineering, and neurotechnologies, many of which have incorporated ideas and techniques from system and control theory. I wish to particularly draw attention to recent theories of the brain, e.g., the free-energy principle (Friston, 2010), that are closely aligned with Kalman's pioneering contributions.

Professor Kalman was very rigorous and logical in his thinking. He subjected various ideas to their full logical conclusions. To illustrate this, consider the following paragraph:

> 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.
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> Page 51, TMST (Kalman et al., 1969)

To be sure, there has been tremendous progress in adaptive control in the past decades, and it is a thriving subfield of control systems. And the dramatic advances in efficacy of machine learning are pointing to even greater progress in adaptive control.

Physics was a subject Professor Kalman admired immensely. He, however, lamented that physics research had diverged from advances in engineering and technology. The following remark illustrates how he thought about the relation between physics and control:

> 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.
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> Acceptance Speech, Kyoto Prize (Kalman, 1985).

And he greatly admired groundbreaking technological advances as illustrated next:

> 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, (Kalman, 1985).

Technological advances continue at ever faster pace. I am sure Professor Kalman would take deep interest in them and draw connections between science and engineering research visions and the technological advances that benefit society.

The above comments also made me think about the emergence of team science as a very important mode for science and engineering research. I wonder about Professor Kalman's views on research advances that involve large multidisciplinary teams.