[3] R. E. Kalman and R. S. Bucy, "New results in linear filtering and prediction theory," *Trans. ASME J. Basic Eng.*, vol. 83, pp. 95–108, Mar. 1961.

[4] R. E. Kalman, "On the general theory of control systems," in *Proc. First Congress I.F. Automatic Control*, Moscow, Russia, 1960, pp. 481–491.

[5] F. M. Callier and J. L. Willems, "Criterion for the convergence of the solution of the Riccati differential equation," *IEEE Trans. Automat. Contr.*, vol. 26, no. 6, pp. 1232–1242, 1981.

[6] H. Kwakernaak and R. Sivan, *Linear Optimal Control Systems*. New York: Wiley, 1972, p. 238.

[7] V. Kučera, "Algebraic Riccati equation: Hermitian and definite solutions," in *The Riccati Equation*, S. Bittanti, A. J. Laub, and J. C. Willems, Eds. Berlin: Springer-Verlag, 1991, pp. 58–88.

[8] W. M. Wonham, "On a matrix Riccati equation of stochastic control," *SIAM J. Control*, vol. 6, no. 4, pp. 681–697, 1968.

[9] B. P. Molinari, "The time-invariant linear-quadratic optimal control," *Automatica*, vol. 13, no. 4, pp. 347–357, 1977.

[10] V. Kučera, "On nonnegative definite solutions to matrix quadratic equations," *Automatica*, vol. 8, no. 4, pp. 413–423, 1972.

[11] V. Kučera, "A contribution to matrix quadratic equation," *IEEE Trans. Automat. Contr*, vol. 17, no. 3, pp. 344–347, 1972.

[12] J. L. Willems and F. M. Callier, "Large finite horizon and infinite horizon lq-optimal control problems," *Optim. Contr. Appl. Meth.*, vol. 4, no. 1, pp. 31–45, 1983.

Kalman's Influence on My Scientific Work: Some Recollections and Reflections

ANDERS LINDQUIST

I first met Rudolf Kalman in Vienna, Austria, in the spring of 1972. I had recently finished my Ph.D. at the Royal Institute of Technology, Stockholm, Sweden, and I was invited to give a talk on my recent results in stochastic control theory at a small workshop that Kalman also attended. Apparently, Kalman was favorably impressed with my talk because he took me out for dinner the same evening and immediately invited me to come to Florida for the coming academic year. Kalman had just moved from Stanford to the University of Florida, and this is how I became his first postdoctoral associate at his new Center for Mathematical Systems Theory in the fall of 1972.

When I first met Kalman, his impressive scientific output had just culminated. He had finished his work on a beautiful algebraic theory of mathematical systems theory; see, for example, [1]. A decade earlier, he had completed a comprehensive theory on what we today call Kalman filtering. At the time, some of Kalman's critics claimed that the results were in the air and that others had derived similar filtering equations before him. I have always claimed that this position is grossly unfair. Kalman filtering is not just a set of filter equations. It is an important part of systems theory that includes a theory for the matrix Riccati equation and provides extensions to many other problems like the inverse problem of optimal control. In fact, Kalman had a very good taste for problems and knew how to formulate them in interesting and beautiful ways. He always wanted to be regarded as a mathematician rather than as the engineer he had been educated to be, and not without reason. Indeed, his approach to problems was that of a mathematician

Digital Object Identifier 10.1109/MCS.2016.2643319
Date of publication: 17 March 2017

Kalman had a very good taste for problems and knew how to formulate them in interesting and beautiful ways.

for which beauty and clarity of principle was paramount. He would identify the underlying mathematical problems and remove secondary considerations often encountered in the engineering literature. He should also be credited with setting standards, canonizing notation, and prescribing an overall style and a rigorous language, which distinguishes the writing of our community from other applied mathematics and engineering communities.

As a scientist, I owe a lot to Kalman. His work on realization theory inspired me to replace the variable in the Szegö polynomial with the system matrix, a trick that eventually led to the paper [2], submitted in fall of 1972, introducing a fast algorithm for Kalman filtering in lieu of the Riccati equation. Moreover, Kalman's early results [3] on the Kalman–Yakubovich–Popov (KYP) lemma became an important building block in my work with Giorgio Picci on stochastic realization theory [4]. More importantly, he has been a role model for me in his way of formulating and looking at problems.

A case in point is the rational covariance-extension problem, formulated by Kalman in [5]. He was obsessed by this problem. He was hardly on the right path, but that matters less. He wanted simplicity and symmetry and was looking for a

 1066-033X/17©2017IEEE

matrix-rank condition for the minimal degree of a partial stochastic realization, akin to the Hankel condition in deterministic partial-realization theory. Today we understand that this cannot be done; see, for example, [6, Thrm. 2.2]. Moreover, because, at this time, he was a firm believer in algebra as the ultimate tool of systems theory, Kalman thought that the solution set could be parameterized by the Schur parameters subject to algebraic constraints, which also turned out to be a dead end. Tryphon Georgiou, one of Kalman's most brilliant students, made the first crack at this problem in his thesis [7] in 1983 using analysis and topology instead of algebra. Inspired by Kalman, and initially oblivious of Georgiou's partial results, I eventually got together with Chris Byrnes to try to solve this problem. This led to a long stretch of research during which we became aware of Georgiou's results via [8]. We finally solved the part missing in [8] in a paper together with Gusev and Matveev [9] and subsequently proposed a convex-optimization approach to the problem [10], after which we joined Georgiou for a long series of papers applying the same principles to several applied problems as well as problems in pure mathematics, for example, generalizing a result of Sarason on generalized interpolation.

At the Center for Mathematical Systems Theory, I also had the pleasure of meeting V.M. Popov from the KYP lemma, who had also been invited to Kalman's center. However, for reasons that are beyond the scope of the present account, Popov soon left the center and moved to the mathematics department during the fall of 1972, as did I shortly thereafter. Altogether, my affiliation with Kalman's center lasted only four months, rather than the full year originally planned, and my discussions with Popov continued in the mathematics department. (The third person in the KYP lemma, V.A. Yakubovich, later became my collaborator and dear friend, and we coauthored five papers.)

Kalman told me many times about his uphill battles. His first paper on Kalman filtering was rejected, and he repeatedly came back to this fact. Instead he had to publish in a less prestigious mechanical engineering journal. This and similar events colored his view of the scientific community and his own place in it. He disliked probabilistic presentations of the Kalman filter where the processes were assumed to be Gaussian. In fact, he considered Kalman filtering a completely deterministic problem. On this point, I happen to agree with him [11].

Like many excellent mathematicians with great achievements in their younger years, Kalman came to look for hard open problems beyond his reach, and much of his efforts during the second part of his life did not lead to substantial scientific results but mostly interesting problem formulations, which, nevertheless, inspired others in the directions that he envisioned. Kalman could have become an even more important asset to the systems and control community had he been more engaged in collaboration and support of young researchers. His insights and good taste for problems would have been a gold mine in such collaborations, as they have been in his written contributions. Indeed, his influence and original thought will be missed.

AUTHOR INFORMATION

Anders Lindquist (alq@kth.se) is Zhiyuan Chair Professor at Shanghai Jiao Tong University, China, and professor emeritus at the Royal Institute of Technology (KTH), Stockholm, Sweden. Between 1972 and 1983, he had a full academic career from assistant to full professor in the United States, after which he was appointed to the chair of optimization and systems at KTH. He is a member of the Royal Swedish Academy of Engineering Sciences, a foreign member of the Chinese Academy of Sciences and the Russian Academy of Natural Sciences, an honorary member of the Hungarian Operations Research Society, a Life Fellow of the IEEE, and a fellow of the Society for Industrial and Applied Mathematics and the International Federation of Automatic Control. He is an honorary doctor at the Technion (Israel Institute of Technology) and the recipient of the 2009 Reid Prize in Mathematics from the Society for Industrial and Applied Mathematics and the 2003 George S. Axelby Outstanding Paper Award from the IEEE Control Systems Society.

REFERENCES

[1] R. E. Kalman, P. L. Falb, and M. A. Arbib, *Topics in Mathematical Systems Theory*. New York: McGraw-Hill, 1969.
[2] A. Lindquist, "A new algorithm for optimal filtering of discrete-time stationary processes," *SIAM J. Control*, vol. 12, no. 4, pp. 736–746, 1974.
[3] R. E. Kalman, "Lyapunov functions for the problem of Luré in automatic control," *Proc. Nat. Acad. Sci. U.S.A.*, vol. 49, no. 8, pp. 201–205, 1963.
[4] A. Lindquist and G. Picci, "On the stochastic realization problem," *SIAM J. Control Optim.*, vol. 17, no. 3, pp. 365–389, 1979.
[5] R. E. Kalman, "Realization of covariance sequences," in *Proc. Toeplitz Memorial Conf.*, Tel Aviv, Israel, 1981, pp. 331–342,.
[6] C. I. Byrnes and A. Lindquist, "On the partial stochastic realization problem," *IEEE Trans. Automat. Control*, vol. 42, no. 8, pp. 1049–1069, 1997.
[7] T. T. Georgiou, "Partial realization of covariance sequences," Ph.D. dissertation, Center for Mathematical Systems Theory, Univ. Florida, Gainesville, FL, 1983.
[8] T. T. Georgiou, "Realization of power spectra from partial covariances," *IEEE Trans. Acoustics, Speech Signal Process.*, vol. 35, no. 4, pp. 438–449, 1987.
[9] C. I. Byrnes, A. Lindquist, S. V. Gusev, and A. S. Matveev, "A complete parameterization of all positive rational extensions of a covariance sequence," *IEEE Trans. Automat. Control*, vol. 40, no. 11, pp. 1841–1857, 1995.
[10] C. I. Byrnes, S. V. Gusev, and A. Lindquist, "A convex optimization approach to the rational covariance extension problem," *SIAM J. Contr. Optim.*, vol. 37, no. 1, pp. 211–229, 1999.
[11] C. I. Byrnes, A. Lindquist, and Y. Zhou, "On the nonlinear dynamics of Kalman filtering," *SIAM J. Control Optim.*, vol. 32, no. 3, pp. 744–789, 1994.