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Kalman Filtering: Past and Present. An outlook from Russia. (On the occasion of the 80th birthday of Rudolf Emil Kalman)

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Abstract—This article is in honor of the 80th birthday of Rudolf Emil Kalman. A brief biography of R.E. Kalman is presented. The most important facts concerned with the creation of the celebrated Kalman filter are briefly outlined. Some trends in the development of applied methods for solution of filtering problems are analyzed. Kalman's relations and contacts with Russian scientists as well as their contribution to filtering theory and its applications are discussed.

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INTRODUCTION

In 2010 the scientific community celebrated the 80th birthday of Rudolf Emil Kalman, one of the creators of modern control and filtering theory. His contribution to this scientific field is generally recognized and widely covered in literature. As far back as 20 years ago, there appeared a book *Mathematical System Theory: The Influence of R.E. Kalman*. It was a festschrift in honor of Professor R.E. Kalman on the occasion of his 60th birthday [1]. It included articles of leading scientists, who described the impact of Kalman's work on different applications of control and filtering theory. Another remarkable book *Control Theory: Twenty-Five Seminal Papers (1932–1981)* edited by Tamer Basar was published in 2001 [2]. It was prepared on the initiative of the IEEE Control Systems Society with the aim to highlight the most significant results obtained in a pivotal period in the history of the development of control theory. The 12-member editorial board of this book consisted of distinguished scientists from different countries. Among the authors of the seminal papers included in this book were H. Nyquist, N. Wiener, L.S. Pontryagin, V.A. Yakubovich, and a number of other world-renowned scientists. It is worthy of note that Kalman was the only scientist to have three papers included in this publication. I would like to emphasize the fact that two of them were written by him at the age of 30 [3–5].

Kalman has visited Russia, where he is highly regarded for his accomplishments, on many occasions. He is acquainted with many Russian scientists. The most important of his articles and books were promptly translated into Russian; they are well known to Russian control theorists [6–10]. In April 2010, a seminar dedicated to the 80th Birthday of R.E. Kalman was held in Moscow by the Institute of Control Sciences of the Russian Academy of Sciences with the assistance of the Academy of Navigation and Motion Control[2], to pay a tribute to the outstanding scientist [11]. On June 2, 2010, the author of this paper made a presentation at the Regular General Meeting of the Academy of Navigation and Motion Control also devoted to the jubilee of Rudolf Emil Kalman. It dealt with two main issues. First, it touched briefly upon the background and consequences of one of Kalman's most important results – the discovery of the recursive optimal estimation procedure that is now known as the Kalman filter. The second subject was concerned with Kalman's relations and contacts with Russian scientists as well as their contribution to filtering theory and its applications.

This article is based upon the materials of the presentation made at the General Meeting of the Academy of Navigation and Motion Control.

BRIEF BIOGRAPHY

Rudolf Emil Kalman was born in Budapest, Hungary, on May 19, 1930. Along with his family, he immigrated to the United States during World War II [1, 12, 13]. He studied electrical engineering at the Massachusetts Institute of Technology (MIT) in Cambridge. Kalman received his bachelor's degree in 1953 and his master's degree in 1954. Later he studied under Professor John R. Ragazzini and in 1957 he received his doctorate degree from Columbia University. From 1955 to 1957 Kalman was employed as a staff engineer at the IBM Research Laboratory. Since 1958 he worked for the Research Institute for Advanced Studies in Baltimore (RIAS). The institute was headed by Solomon Lefschetz (1884–1972), a Russian-born

The text was submitted by the author in English.

[2] The International Public Association *Academy of Navigation and Motion Control* was founded in February 1995 as a public association of scientists and researchers in the field of navigation and motion control.

Fig. 1. @

American mathematician, whom Kalman regarded as one of his mentors [14]. Kalman started working in RIAS as a research mathematician and later he became an associate director of research. While at the Institute (1958–1964), he was involved in fundamental research in systems analysis and control theory. In 1964 Kalman moved to California to assume a professorship at Stanford University, where he worked in the departments of electrical engineering, mechanics, and operations research. In 1971 he became a Graduate Research Professor and director of the Center for Mathematical System Theory at the University of Florida. Starting in 1973, he also held the position of chair for Mathematical System Theory at the Swiss Federal Institute of Technology in Zurich.

Kalman has received many honorary awards, prizes and medals. He was awarded the IEEE Medal of Honor in 1974, the IEEE Centennial Medal in 1984, the Inamori foundation's Kyoto Prize in High Technology in 1985 (a Japanese award similar to the Nobel prize), the Steele Prize of the American Mathematical Society in 1987, the Richard E. Bellman Control Heritage Award in 1997. Among the latest awards, in January 2008 he received the Charles Stark Draper Prize for "the development and dissemination of the optimal digital technique (known as the Kalman filter) that is pervasively used to control a vast array of consumer, health, commercial and defense products". On October 7, 2009, Kalman received the National Medal of Science in the White House from U.S. President Barack Obama.

Kalman is a member of the U.S. National Academy of Sciences, the American National Academy of Engineering, and the American Academy of Arts and Sciences. He is a foreign member of the Hungarian, French, and Russian Academies of Science.

PREHISTORY OF THE KALMAN FILTER

Reviewing the events that led to the creation of the Kalman filter, it seems appropriate to cite the words of Kalman himself: "As I have mentioned on numerous occasions (see Ref.8, page 13)[3], the discovery of the Kalman filter (January 1959) came about through a single, gigantic, persistent mathematical exercise. It was not my well-earned reward after long years of relentless research. (The acknowledgment of partial support in my first publication [9][4] referred to an umbrella grant to a large, heterogeneous group; this grant was not specifically related to the filtering problem.) Just as Newton was lucky having timed his birth so as to have Kepler's laws ready and waiting for him, I was lucky, too" [14].

The literature on the history of the development and elaboration of filtering theory is abundant, see [1, 12, 15–17], for example. Of particular interest is the survey of T. Kailath, a famous filtering theoretician [17], which includes 390 references. A distinguishing feature of this work is that, unlike many other similar publications, the author gives quite a balanced description of the contribution to filtering theory of both foreign and Russian scientists.

Now, let us consider the milestone events that are directly connected with Kalman's first publication devoted to his famous filter [3].

When speaking about Kalman's predecessors in the development of estimation theory, the names that come to mind first are the German mathematician Carl Friedrich Gauss (1777–1855) and the French mathematician Adrien-Marie Legendre (1752–1833), whose names are associated with the discovery of the least squares method.

It was at the age of 18 (1795) that Gauss applied the least squares method, but he did not publish it. Quite independently of him, Legendre invented a similar method in 1806 and published the results he obtained [15–17]. Both scientists claimed their priority in creating this method. However, eventually historians gave priority to Gauss.

Also, I must mention two other scientists who were the predecessors of Kalman: A.N. Kolmogorov (1903–1986), the outstanding Soviet mathematician, one of the founders of the modern probability theory, and N. Wiener (1894–1964), the great American mathematician whose name is usually associated with the origination of cybernetics.

Like Gauss and Legendre, Kolmogorov and Wiener worked on similar problems. Whereas at the beginning of the 18th century Gauss and Legendre

[3] See Ref.12 in this paper.
[4] See Ref. 3 in this paper.

Fig. 2. Carl Friedrich Gauss (1777–1855).

Fig. 3. Adrien-Marie Legendre (1752–1833).

dealt with the estimation problem of time-invariant vector, Kolmogorov and Wiener solved the problems of time variant parameter estimation. To be more exact, Kolmogorov considered scalar stationary random sequences. Assuming the correlation functions for a sequence under estimation to be known, Kolmogorov derived expressions for the minimal values for the error variances of linear interpolation and extrapolation estimates. He first published these results without a proof in 1939 [18]. More detailed results were presented in 1941 [19].

As Wiener worked on a defense project, the results he obtained in this field only came to light in 1949 [20]. As distinct from Kolmogorov, Wiener considered the problem under the following assumptions: signal and noise are scalar continuous stationary random processes; correlation and cross-correlation functions for random processes are known; observation interval is semi-infinite; spectral densities for signal and noise are rational functions.

He derived an estimation algorithm in the form of convolution of observations with the weight function, which, in its turn, satisfied the integral equation of Wiener and Hopf. The problem was solved on the basis of factorization of rational spectral densities. It is pertinent to note that Chapter 3 *The linear filter for a single time series* from Wiener's book *Extrapolation, interpolation and smoothing of stationary time series, with engineering applications* [20] was also selected for [2].

Kalman was not satisfied with the problem statement and the solution derived earlier. He did not quite agree with the assumption that statistical characteristics, like the correlation function, are the correct way of describing uncertainties, and also with the idea that describing a system with the transfer function is exactly the same as representing a system itself [14].

In this connection he wrote: "Soon I noticed serious flaws in Wiener's formulation. Two of these flaws were the following:

1) He took it for granted that statistical gadgets (like the time-correlation function) are the right way to encode quantitative uncertainty.

2) He was under the impression that a system description (like the transfer function) is exactly the same as a system in a concrete physical sense" [14].

Besides, the suggested algorithms were not quite convenient in solving applied problems, in particular, those solved with the use of computers, which were

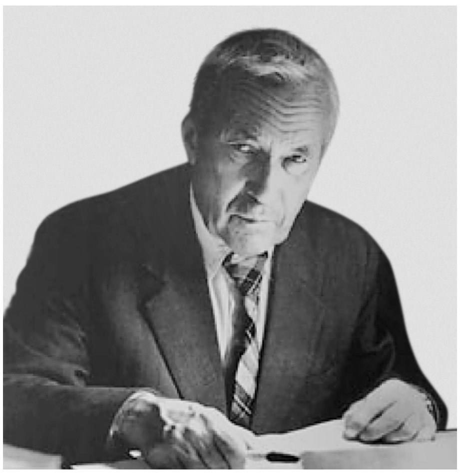

Fig. 4. A.N. Kolmogorov (1903–1986).

Fig. 5. N. Wiener (1894–1964).

Fig. 6. R.L. Stratonovich (1930–1997).

beginning to find wide application. A significant restriction was the assumption about the stationary character of processes and the fact that the solution was derived for an infinite observation interval.

While still a student, and later on for about 10 years, Kalman worked hard to reveal relations between transfer functions and linear vector differential equations. In the early 1960s Kalman concluded that "Linear systems described by a transfer function matrix $\rightleftarrows$ linear vector differential equations (which are completely controllable and observable)" [14].

KALMAN FILTER. THE FIRST PUBLICATION

By the end of the 1950s Kalman had already obtained some results on describing systems in state space for problems of control theory. The idea of using this approach to the solution of Wiener filtering problems came to Kalman at the end of November 1958, late in the evening, when he was returning to Baltimore from Princeton. It was in April 1959, in Cleveland that Kalman first propounded this idea [12]. His first paper "A New Approach to Linear Filtering and Prediction Problems" was published in 1960 [3]. It is interesting to note that the article appeared not in an electrical engineering journal, traditional for this kind of problems, but in the Transactions of the American Society of Mechanical Engineers (ASME). The problem was that the electrical engineering and systems engineering communities were skeptical of the ideas on filtering stated in that article, and so the publication could have been delayed. One of the editorial notes to this publication said: "Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society" [3]. It was precisely the paper of which it would later be written: "This paper by Kalman ... could easily be considered as the paper that marked the beginning of a new era in filtering and prediction" (H. Kwakernaak and T. Basar from the preamble to [3] in [2]). In that paper Êalman suggested an algorithm for solving the Wiener filtering problem, which is now known as the Kalman filter. The proof of the results obtained was based on the orthogonal projection theorem, at that time known mainly to mathematicians. Although the sequences to be estimated and observations in this article were assumed to be Gaussian, it followed from the arguments that the suggested algorithm remained optimal in the class of linear algorithms for non-Gaussian sequences. This very important property is often forgotten, although it is precisely this feature that makes the Kalman filter effective in solving applied problems. The duality theorem, which establishes the relationship between the filtering and control problems, was also proved in this paper.

In Kalman's opinion, "...this was a true discovery because of the following:

1) No one imagined that the end result would be That simple?!...

2) No one expected the result to be That general (no restrictions like infinite time interval, constant coefficients, etc.).

3) Every one was happily surprised that it turned out to be That useful.

... Of course, I was well aware how very, very important this discovery was. I even tried to explain it to my girlfriends. But, honestly, I didn't quite imagine that it will turn out to be That important" [14].

Before proceeding with a brief discussion of the impact the first work had on the development of filtering theory and its application, I would like to turn the reader's attention to another note made by Kalman himself for the publication [3]. It concerned the linearity of the proposed algorithm. Kalman wrote: "Of course, in general these tasks may be done better by nonlinear filters. At present, however, little or nothing is known about how to obtain (both theoretically and practically) these nonlinear filters" [3]. In this connection, it should be pointed out that the Soviet scientist R.L. Stratonovich (1930–1997) had by that time found a practical solution of the optimal nonlinear filtering problem, based on his own theory of conditional Markov processes.

Stratonovich was born in Moscow on May 31, 1930. He would have been 80 in May, just like Kalman. He passed his final school examinations without attending classes, and was awarded a gold medal as a sign of honors. In 1947 he enrolled at the Physics Department of Moscow State University. Later he became a professor at this university, where he worked all his life [21, 22]. For filtering problem solution, Stratonovich derived partial differential equations for the a posteriori probability density function, which is needed for calculation of the optimal estimate. In the discrete-time case, their analog is the recursive relation for this density [23]. The Kalman-Bucy filter [7] for continuous time can be derived as a particular case corresponding to the Gaussian linear estimation problem. Unfortunately, in spite of the outstanding results Stratonovich obtained [24–26], his accomplishments in the field of filtering theory have not been appreciated according to their merits.

DEVELOPMENT OF APPLIED FILTERING ALGORITHMS

After Kalman's first paper on solution of the filtering problem based on the state space approach was published, this field began progressing rapidly. Kalman found fertile ground for application of his algorithm at the NASA Ames Research Center and Charles Stark Draper Laboratory (the former MIT Instrumentation laboratory). He visited the Ames Research Center in autumn 1960 and met S.F. Schmidt, who is believed to be the first to have applied the Kalman filter (KF) to the solution of practical problems. In the mid-1960s, due to Schmidt's effort, KF became a part of a navigation system for the C5A air transport. It was used in integrated processing of data from the inertial system and radar, and in so doing, it rejected measurements with large errors [12, 27].

R. Bucy, who also worked for the Research Institute for Advanced Studies in Baltimore (RIAS), suggested to Kalman that they work together to find a relationship between the Wiener-Hopf equation and the Riccati equation in KF for continuous time, which was done in their joint paper [7]. In particular, it was shown that the Riccati equation can have a stable solution, even in the case when the initial system is unstable, provided it is controllable and observable.

Using KF for applied problems faced a lot of difficulties, such as: the problem of choosing models that could afford adequate description of the signal being estimated and the measurement error; the problem of algorithm sensitivity to models being chosen; the problem of the amount of computations for suboptimal filtering algorithms; the problem of simplifying models for measurement errors and generating noises; the problem of computational stability of the procedures suggested, etc. The development of Kalman's ideas and the solution to these problems have been addressed in numerous publications [1, 17, 31].

Much attention has been given to various modifications of the KF, adaptive algorithms, nonlinear problem solutions [1, 27–37]. The extended KF, known as the Kalman-Schmidt filter in early publications, is also widely used nowadays [27]. The so-called iterative filters and higher-order filters, which are various modifications of Kalman-type algorithms, were suggested later [12, 35–37]. Solution of nonlinear problems with essential nonlinearities called for the development of algorithms based on various approximations and recursive relations for a posteriori probability density function. The best known of these algorithms are the point-mass method, the method based on Gaussian mixture approximation of a posteriori density, the partitioning method, the Monte-Carlo method, etc. [16, 38–42]. Till the late 1970s filtering theory and its applications were progressing rapidly.

It should be noted that the Soviet, and later, post-Soviet Russian scientists made a significant contribution tî filtering theory and the development of applied filtering algorithms. Besides R.L. Stratanovich, it is also necessary to mention R.Sh. Liptzer, A.N. Shiryaev, V.S. Pugachev, V.I. Tikhonov, N.K. Kul'man, V.N. Fomin, A.B. Kurzhanski, M.S.Yarlykov, Yu.G. Sosulin, M.A. Mironov, A.K. Rozov, et al. [23, 31–33, 43–47].

Among the many applications where filtering algorithms are widely used, I will point out two. One of them is the development of communication and radio systems, including radionavigation systems. As a rule, the problems were considered here for continuous time. The other application is connected with navigation, guidance, and tracking, which deal with both continuous-time problems and their discrete variants. It should be emphasized that the part of the collection of papers published on the occasion of Kalman's 60th birthday

[1] devoted to applications of the Kalman filter was illustrated by navigation problems [48]. In Russia this line of research was followed by A.A. Krasovski, I.A. Boguslavski, I.N. Beloglazov, S.S. Rivkin, I.B. Chelpanov, S.P. Dmitriev, R.I. Ivanovski [49–54], and many others. More detailed information about the contribution of Russian scientists tî filtering theory and the development of applied filtering algorithms can be found in the references of the cited literature. Unfortunately, no comprehensive survey on the development of applied filtering theory in the field of navigation and guidance has been done yet, as it was done by V.I. Tikhonov for radiotechnical applications [31–33].

By the mid-1980s interest in the development of filtering algorithms had waned; and it was only in the mid-1990s that it revived again due to the need to solve more sophisticated navigation problems, as applied to unconventional vehicles and robots, and also owing to considerable progress in the development of computers.

In my opinion, today there are two main lines in the development of new filtering algorithms intended for applied problems.

One of them is Kalman type algorithms: regression filters, UKF-filters (unscented Kalman filter) or sigma-point filters [55–59]. They all are based on a rather simple idea of replacing the calculation of derivatives in linear representation with procedures similar to stochastic linearization. Logically, these algorithms are connected with the problem of designing linear optimal algorithms for nonlinear non-Gaussian systems [58, 60]. It should be noted that a linear optimal algorithm in a linear problem for a non-Gaussian case reduces to a conventional Kalman filter, which, as it was mentioned above, is discussed in [3]. However, in the nonlinear problem, this kind of algorithms involves numerical integration to determine the covariance for measurements and cross covariance for measurements and a sequence under estimation [58, 61]. Various modifications differ from each other by the simplification methods used to calculate these integrals, which are used for linear representation of equations for the state vector and measurements. It is fair to say that the procedure of stochastic linearization was suggested for filtering problem earlier; in particular, it was described in [36], which cites the first publications concerned with the development of this procedure. But at that time no account was taken of an additional error resulting from replacement of the nonlinear function for its linear analog.

The other line is also connected with the development of nonlinear filtering algorithms. The problem of calculating an estimate and the corresponding covariance matrix for discrete time is, generally speaking, a problem of calculating multiple integrals with the use of a recursive relation for the a posteriori density [41, 42]. Considerable progress in this area came with the development of algorithms based on sequential Monte-Carlo methods [62, 63]. It is worthy of note that one of the first fundamental works in this field by V.S. Zaritsky, B.V. Svetnik, and L.I. Shimilevich was published as early as the mid-1970s in the Soviet Union [64].

The engineering community still continues the debates about the relation between the Wiener and Kalman filtering algorithms. The followers of frequency-domain methods, which are extensively used in Wiener filtering, insist on the advantages of these algorithms, whereas those who make use of state space techniques defend the merits of the Kalman filter. These two variants of filtering problem solutions are compared from the standpoint of theory in various publications, see [30], for example. Here, it is pertinent to note the following important and generally recognized issues. An indisputable advantage of the Kalman filter is the possibility to solve problems of optimal nonstationary filtering of Markov processes for finite time. For stationary filtering problems in the steady-state mode, both approaches result in the same solution for the same problem. It is a matter of liking whether to choose this or that approach in solving these problems; the preference often depends on a school to which the scientist or engineer belongs. In the case when a researcher has to deal with stationary problems in practice, the frequency approach is definitely advantageous owing to its clearness and simplicity: in some situations it is possible to consider various combinations "by hand" without using a computer. The designers of technical systems fully realize how difficult it is to go from elegant formulas to an operable algorithm. This is, by the way, true for any more or less complicated algorithms. The successful implementation of this or that type of algorithms depends, first of all, on how much the chosen approach fits the problem being solved. At the same time, the possibility of implementing an algorithm depends significantly on a designer's persistence and competence. It can be said with assurance that engineers and designers who have a good command of both Kalman and Wiener algorithms have the advantage over specialists who have mastered only one of these approaches.

In this regard I wish to mention the talented Russian scientist Leonid P. Nesenyuk, who, unfortunately, passed away prematurely. He knew well how to handle these two methods in practice, as applied to navigation. He has obtained a number of results that allowed a better insight into their interrelation and made it possible to appreciate both of them [65].

"THE DARKER SIDE"

The title of this small section is borrowed from the title of a part of Kalman's paper [14]. Here, we are dealing with the evolution of Kalman's views. Starting from the 1970s, Kalman has strongly questioned the validity of the stochastic method for describing signals in the solution of applied problems.

In particular, in the introduction of his presentation at the conference devoted to the 50th anniversary of

Steklov Mathematical Institute in Moscow in 1984 he said that he was deeply impressed by the idea of Academician L.S. Pontryagin, formulated by him in October 1969 in Stanford, that mathematicians do not trust probability [9]. That made him ponder over this idea. Kalman writes that the least squares method should be treated as the main mathematical instrument rather than a theory for estimation in noise conditions. He shares Pontryagin's viewpoint and is happy to do mathematics without taking anything on trust. He thinks that nature does not obey the rule of conventional probability, but it does not rule out uncertainty.

Later in another paper Kalman also remarks: "...A random process is an abstract mental construct, not something that can be pieced together from measurements. Procedures for determining parameters for a random process are indirect. If a random process exists in the axiomatic sense used in Ref. 9[5] – and there are some, including the present writer, who may deny this – then all is well with the Kalman filter because it is all mathematics. If not, the question is very much open. The burden rests on those who want to apply the Kalman filter at all costs..." [14].

Indeed, everybody who is going to apply Kalman's filter "at all costs" should bear responsibility for the results. However, it should be emphasized that despite some evident shortcomings of the probabilistic approach, justly noticed by Kalman, the algorithms designed in the context of this approach are rather effective and extensively used to solve various applied problems. In this connection, it seems appropriate to mention the fact that some algorithms, which were originally designed in the context of the stochastic approach, can, in principle be validated from a standpoint that does not rely on probability theory.

RELATIONS WITH RUSSIA

Kalman is acquainted with the leading Russian scientists. He came to the Soviet Union and later Russia many times: Moscow in 1960, 1984, 2006 [6, 9, 69], Yerevan in 1968 [67], Tbilisi and Kiev in 1969 [68], St. Petersburg in 1970, 2006 [69].He became acquainted with many Russian scientists at the First World IFAC Congress on Automatic Control held in Moscow in 1960. It was there that he first met R.L. Stratonovich. It is known that they corresponded for some period of time [21]. He made the acquaintance of the outstanding Soviet mathematician L.S. Pontryagin (1908–1988) the same year. Later, they had closer contacts in Tbilisi in 1969 and after that Pontryagin was invited to the United States on Kalman's initiative [70].

Kalman also met Academician Ya.Z. Tsypkin (1919–1997) [71], starting with their acquaintance in Heidelberg in 1956, then in Moscow in 1960, and at various scientific conferences. It was Tsypkin who edited the Russian translation of Kalman's book *Topics in Mathematical System Theory* [8].

Kalman was in correspondence with Professor À.I. Lurie (1901–1980), which follows from the references in [5]. He was acquainted with Academician V.S. Pugachev (1911–1998) [13, 44].

At the present time, Kalman is on friendly terms with Academician A.B. Kurzhanski, the chairman of the Russian National Committee on Automatic Control, who is known for notable results in the field of filtering theory [46], and Professor of St. Petersburg University V.A. Yakubovich. Specialists are familiar with the Kalman-Yakubovich-Popov lemma (known as the KYP lemma), which establishes a link between the frequency methods in control theory and the methods of Lyapunov functions. It was published in 1962 [72]. This article, which is only 4 pages long, was also included in a special volume of the 25 best publications in control theory [2]. It provided the basis for the future significant investigations in this field [73]. Kalman succeeded in obtaining similar results independently a year later, using the notions of controllability [74].

When asked about the event or visit to Russia that was the most memorable for him, Kalman answered that it certainly was his first visit to Moscow, namely, participation in the First IFAC Congress on Automatic Control [75]. It was undoubtedly an outstanding event for science of the day. The Congress was held in 1960 from June 27 to July 7, with the 1190 participants and more than 1000 invitees from 29 countries. 285 papers were selected from the total amount of 410. B. Widrow, the famous scientist, the founder of adaptive filter theory, writes about his impressions of this Congress in [76], which is worth reading. How important the congress was for our country can be judged by the fact that it was opened by A.N. Kosygin, Deputy Chairman of the USSR Government [75, vol.1]. The reasons why the congress was held in Moscow, and nowhere else, are quite clear if we remember about the progress the USSR had made by that time in the field of cosmonautics (astronautics): October 4, 1957 – launching of the first artificial Earth satellite; January 2, 1960 – the first flight to the Moon; September 14, 1960 – the first landing of the Luna-2 space vehicle on the lunar surface; October 7, 1960 – the first flight around the Moon by the Luna-3 space vehicle and the first pictures of the back side of the Moon. And, lastly, April 12, 1961 – World's first human spaceflight, with Yuri Gagarin as the first cosmonaut. It is obvious that the development of cosmonautics called for the solution of challenging problems associated with control theory and signal processing. The accomplishments of Soviet scientists in this field were generally recognized.

A unique feature of the first Congress was that it may have been the only case when presentations were translated synchronously into four languages: English, Russian, German, and French. A group of translators had been trained specially for this occasion. It is interesting to note that Kalman's presentation "On the

[5] See Ref. 3 in this paper.

Fig. 7. Congress participants, Moscow, 1960.

general theory of control systems" [6] was translated by A.G. Butkovsky, who later became an outstanding scientist, one of the founders of the theory of control for distributed parameter systems. Since 1975 he has been head of a research laboratory in this field in the Institute of Control Sciences of the Russian Academy of Sciences (Moscow) [66].

On one of the days of the congress (June 28, 1961), it was possible to attend specially organized lectures with simultaneous translation into Russian at the Polytechnic Museum. The lectures were delivered in the following order: S. Lefschetz, R. Kalman, N. Wiener. As Kalman recollects: "I was very proud in being so sandwiched in between my intellectual (but not biological) forefathers." Here, you can see a rather unique photo of the congress participants.

The history of this photo is worth telling. In 2005 the 16th IFAC Congress was held in Prague, where Kalman presented a plenary paper "The Evolution of System Theory: My Memories and Hopes". This event was commented in the IFAC Newsletter (2005, no. 5): "There was no chair left in the Congress Hall of the Prague Congress Center as everybody was eager to see and hear the living legend of System Theory." E.N. Rozenvasser, a famous Russian scientist, attended the Congress in Prague too. As it turned out, he was also a participant of the First IFAC Congress in Moscow. So, when they met in Prague in 2005, Rozenvasser showed Kalman a photo with the participants of the Congress.

When I was preparing presentation for the Regular General Meeting of the Academy of Navigation and Motion Control, I remembered this story and asked Rozenvasser for that photo, but he said that, unfortunately, it had been lost. However, he remembered that he had given it to the organizers of the Prague congress to have a copy taken. I got in touch with M. Simandl, a famous scientist in filtering theory from the Czech Republic, co-chair of the International Program Committee of the 16th IFAC Congress, with a request to send me a copy of this picture or some other photos from the First Congress with Kalman, if possible. Shortly after this, I received several photos from Simandl, who had managed to receive them from the IFAC secretariat. Among the others, there was the picture published here, but they wrote that, unfortunately, they did not have any photos with Kalman. However, I was lucky to find Kalman in one of the pictures (see the photo above) and Kalman confirmed that it was he. Kalman is the second on the left in the third row. Moreover, Kalman called the names of the people sitting next to him: "On my right, with head bent down, is Dr. Robert W. Bass, an old friend from Baltimore and Princeton. On my left, in a light suit and glasses, is Dr. John Bertram, who was a doctoral student at Columbia at the same time as I; on his left, in a dark suit but no glasses, is Dr. Phillip Sarachik, who was also a Columbia doctorate student concurrent with me and Bertram".

Now, closing the section devoted to Kalman's relations with Russia, I would like to note that for most people of my and previous generations in our country, famous foreign scientists seemed to be unreal, just a sort of symbols. It is needless to say that their accomplishments existed apart from real people. To be sure, that was the result of the "iron curtain" and, as a consequence, the lack of direct links with foreign colleagues. The situation has drastically changed recently. The impetus for me to perceive that Rudolf Kalman is our contemporary was his paper [14] published in the Russian journal *Aviakosmicheskoe priborostroenie (Aerospace Engineering)* (edited by G.N. Lebedev) in 2004 [77]. And not just the paper itself, but the fact that it was translated and edited by K.K. Veremeenko, a colleague of mine at the Academy of Navigation and Motion Control, Professor of Moscow Aviation Institute, who, as it turned out, was in close touch with Kalman by e-mail while working on that translation. It was later, in 2005, in Prague that I got acquainted with Kalman, and the latter even autographed the above-mentioned journal. And finally, Kalman transmuted in my eyes from an abstract legendary person into a real outstanding scientist during his latest visit to Russia (Moscow and St. Petersburg) in June 2006, which was made possible owing to Academician A.B. Kurzhanski.

In Moscow Kalman was received by N. Plate, the Vice-President of the Russian Academy of Sciences. Kalman visited Zvesdny gorodok (Star City)—the city of cosmonauts—and delivered a lecture at Moscow State University. He also paid a visit to Steklov Mathematical Institute. In St. Petersburg Kalman met with Academician V.G. Peshekhonov, the President of the Academy of Navigation and Motion Control, the Chairman of St. Petersburg group of the National Committee on Automatic Control, and Professor V.A. Yakubovich. Kalman delivered a memorable lecture in the House of Scientists, which aroused deep interest among the audience [69].

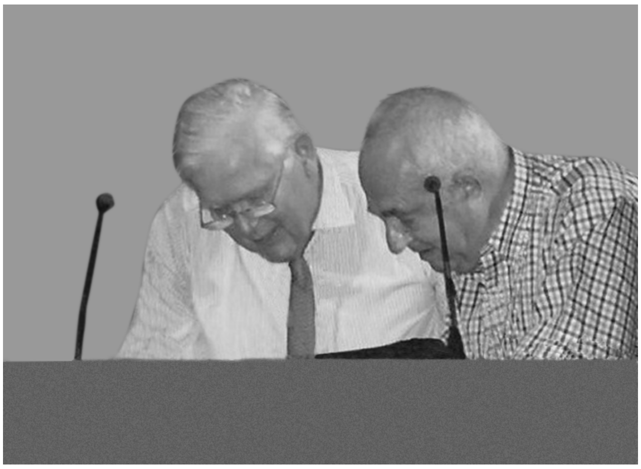

Fig. 8. R.E. Kalman and E.N. Rozenvasser, Prague, 2005.

CONCLUSIONS

Speaking with journalists on the occasion of his receiving the Kyoto Prize in 1985, Kalman said that once he had read the following statement in one of the Colorado Springs pubs [12]: "Little people discuss other people. Medium people discuss events. Big people discuss ideas". I do not know for sure from which context it was taken and what exactly Kalman meant by the word "big". But I think that those who know his works have no doubt that Kalman himself is really big, and in this context it means outstanding.

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