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Adaptive and Robust Control in the USSR [★]

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Abstract: Control theory in the USSR after WW2 achieved serious successes in such fields as optimal control, absolute stability, delay systems, pulse and relay control. Later there was a huge peak of breakthrough research on adaptation, learning and pattern recognition, starting at 1960th. Next approach to control under uncertainty relates to robustness; the results here are also deep and pioneering. The contributions to all these fields were due to Feldbaum, Aizerman, Lerner, Tsypkin, Yakubovich and their coauthors and colleagues. We try to survey the main stages of this fascinating competition.

1. INTRODUCTION

History of adaptive and robust control and more generally of control under uncertainty, including such topics as machine learning, identification etc. in the USSR encounters many bright inventions, theoretical contributions, novel applications. We attempt to highlight the main stages of the history, focusing mainly on the period 1960–1970th. Section 2 deals with "prehistory" — post-war development of the classical control theory. Later the main researchers of this period have been involved in the search of new approaches to "nonclassical" control problems. These results will be discussed in Section 3. Section 4 is a brief survey on later period of sensitivity and adaptation ideas and comparison with robustness approach.

More details on the history of machine learning a reader can find in Fradkov [2020] while more information on Ya.Tsypkin's contribution is contained in Polyak [2020].

Of course we are unable to present the detailed picture of the rich scientific life in the whole field of adaptation and related problems. Our references do not pretend to be full, and comparison with Western research is unsufficient. We hope to see such studies later.

2. CONTROL THEORY IN THE USSR AFTER WW2

Control theory in post-war USSR achieved serious successes. Journal *Avtomatika i Telemekhanika (Automotion and Remote Control)* (established 1936) was the first one in the world devoted to automatic regulation, and the *Institute of Automation and Remote Control* (now *Institute for Control Science*) in Moscow, was also founded before the WW2. In 1946 the famous seminar headed by A.A.Andronov started its activity in the institute, and it immediately attracted bright young researchers like M.A.Aizerman, A.A.Feldbaum, Ya.Z.Tsypkin, M.V.Meerov, B.Ya.Kogan and many others. They made pioneering contributions to many fields of control theory. Aizerman and Lurie developed *absolute stability theory* — the first approach to robust stability for a class of nonlinear systems. Feldbaum and Lerner considered the first examples of *optimal control* problems. Tsypkin introduced the notion of *stability degree*, obtained results on *stability of delay systems* and started research of *pulse and relay systems*. Most of these results had been summarized in the huge volume Solodovnikov [1954] (1117 pages!), written by the collective of authors, including most prominent researchers in the field. This publication of 1954 (known as *THE BOOK*) became top level standard of control theory in USSR. Moreover several textbooks (described in Polyak [2006]) popularized these scientific achievements and made them available for students.

At the beginning of 1960th new directions for research arised. *Optimal control* theory achieved its maturity due to activity of mathematicians (*Pontryagin maximum principle*), while Rozonoer explained the results for engineers on their language. Letov caught the ideas of *linear-quadratic control* by Bellman and Kalman. *Stochastic problems* were studied by Pugachev. New results on *absolute stability* were presented by Aizerman, Gantmakher, Pyatnitsky and Yakubovich.

However at the same time the leading researchers feeled some desire to find new problem formulations and new approaches. As Ya. Tsypkin wrote at 1965 (the text is repeated in Introduction to Tsypkin [1971]):

"Three characteristic periods can be distinguished in the development of the theory of automatic control. For convenience, they are briefly called the periods of determinism, stochasticism and adaptivity.

In the happier days of determinism, the equations describing the states of the controlled plants as well as the

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external actions (functional or perturbing) were assumed to be known. ...

A less happy time came with the period of stochasticism. In considering more realistic operating conditions of the automatic systems, it was established that the external actions, and especially the external perturbations, were continuously varying in time and could not be uniquely defined in advance. ...

At the present " long-suffering" time (from the standpoint of automatic control theory), we become more convinced each day that in the modern complex automatic systems which operate in the most diverse conditions, the equations of the controlled plants and the external actions (or their statistical characteristics) are not only unknown, but that for certain reasons, we do not even have the possibility of determining them experimentally in advance. ... The terms adaptation, self-learning and learning are the most fashionable terms in the modern theory of automatic control. Unfortunately, these terms, as a rule, do not have a unique interpretation and frequently have no interpretation at all".

Beyond scientific reasons, there were political and social circumstances contributing to search of new themes for research. Soviet society was in the period of the so called "Thaw" (Warming) during Khruschev's rule. The 1960s were the years of enthusiasm with respect to *cybernetics.* Cybernetics was becoming a fashionable term, lectures and discussions on cybernetics took place everywhere around. New journals, new departments, new seminars related to cybernetics were organized in many universities both in the Soviet Union and abroad. There was a common feeling that cybernetics is able to make revolutionary changes in the evolution society, not only in science.

3. ADAPTATION, LEARNING, SELF-LEARNING

And indeed the period of 1960th became the time of new searches. It is interesting to see that most of leading control experts completely changed their direction of research trying to respond new challenges.

Feldbaum has published the series of papers on *dual control* Feldbaum [1960]. His idea was that in real-life applications, where parameters of the plant are not known a-priori, control action should play the dual role — it should serve for identification and control simultaneously. Feldbaum tried to find *optimal* control of this kind; the problem happened to be extremely hard. For instance in one of the papers Feldbaum [1960] the author examines the following problem. Given the measurements

$$y_i = (u_i + v_i - \mu)^2, \quad i = 1, \dots N$$

where u_i are controls to be chosen, v_i are random i.i.d. variables with known distribution and μ is unknown scalar parameter. The goal is to design control strategy to achieve minimal mathematical expectation of y_N. However the calculations of optimal control are so complicated, that the author fails to present the algorithm in explicit form. Nevertheless the main idea on dual role of control is highly productive, and this work of Feldbaum was later included in the list of "Twenty-five seminal papers in control" Basar [2001].

The interest of M. A. Aizerman and his coauthors E.M. Braverman, L.I. Rozonoer was focused not on control itself, but on so-called *pattern recognition* or *machine learning* problems. The first publication on practical attempts to solve pattern recognition problems relates to 1962, while general problem formulation was presented in several papers at 1964, see e.g. Aizerman et al [1964]; later the results were summarized in the book Aizerman et al [1970]. Surprisingly this book, full of inspiring ideas and novel applications, has been never translated into English. Their approach was based on *method of potential functions*, that is separation of objects was performed not in the original space of parameters but in the transformed space defined by the potential function (or by a *kernel*).

Novel approach to machine learning theory has been proposed by A.Ya. Lerner, V.N. Vapnik and A.Chervonenkis. They started with the notion of *generalised portrait* Lerner and Vapnik [1963], but the maturity the approach reached after development of the deep statistical theory based on notions of empirical risk and so called *Vapnik-Chervonenkis (VC) dimension.* This lead later to the *SVM (Support Vector Machine) algorithm*, which became one of the most powerful tools in modern machine learning theory and applications. It is interesting to note that V.Vapnik, one of the most cited authors in natural sciences, submitted his latest survey Vapnik [2019] to the same journal *Automation and Remote Control*, where his first paper Lerner and Vapnik [1963] appeared 56 years ago!

The researches on machine learning are closely related to the simplest *identification problem*, that is to *parameter estimation* for static plant. It can be described by the linear model

$$y_i = c_*^T x_i + v_i \tag{1}$$

where $y_i \in R^1$ are measured outputs, $c_* \in R^n$ are static parameters to be estimated, $x_i \in R^n$ are known inputs and v_i are random noises. In statistical terminology, this is the *linear regression* problem. There are several approaches to its solution. If all pairs $y_i, x_i, i = 1, \dots N$ are given and v_i are i.i.d. variables with known distribution, one can apply statistical methods such as *maximum likelihood*, i.e. find estimate c_N for c_* as

$$c_N = \arg\min \sum_{i=1}^{N} F(y_i - c^T x_i), \quad F(t) = -\log p(t) \tag{2}$$

where $p(t)$ is the common density of noises v_i. For instance, in the Gaussian case this estimate transforms into *the least square method*, $F(t) = t^2$. Another situation is met when data are coming on-line. Then estimates c_i are constructed in recurrent form, for instance

$$c_i = c_{i-1} - \gamma_i x_i \phi(y_i - c_{i-1}^T x_i), \quad \phi(t) = F'(t). \tag{3}$$

This is the *recurrent version* of the maximum likelihood method. Step-sizes γ_i can be chosen in different manner, but to guarantee convergence c_i to c_* in some probabilistic sense they should satisfy conditions like

$$\gamma_i > 0, \quad \sum_{i=1}^{\infty} \gamma_i = \infty, \quad \sum_{i=1}^{\infty} \gamma_i^2 < \infty.$$

Similar recurrent estimates can be applied in numerous estimation and identification problems, in stochastic optimization, machine learning and many other applications.

Tsypkin [1971] was the first who recognized wide applicability of such recurrent procedures and their links with *stochastic approximation method* by Robbins and Monro [1951]. He also clarified close relation of this approach with the techniques of Aizerman et al [1964] and Lerner and Vapnik [1963] for pattern recognition. Rigorous validation of the algorithms (3) has been provided in Polyak and Tsypkin [1973], and estimates for the convergence rate are obtained in Polyak and Tsypkin [1979]. New version of the algorithm was proposed in Polyak [1990], it is based on *averaging* of iterations and guarantees acceleration of convergence.

New cycle of research by Tsypkin and his colleagues relates to *statistical robustness* of the proposed iterative estimates. Recurrent version of the maximal likelihood method (3) exploits the density of probability distribution of noises $p(t)$ for the choise of function $\phi(t)$. However this distribution is often unknown; if we assume it to be Gaussian (and take $\phi(t) = t$), then the presence of outliers can lead to strong degradation of the estimates. The idea of *robust estimation* became highly popular in statistics due to works of Box, Huber and others. Robust versions of algorithms (3) was presented and validated in Polyak and Tsypkin [1980].

A related yet different approach to adaptation and learning was developed in *Leningrad State University* (later in 1991 the historical name - Saint Petersburg was returned to the city) by Vladimir Yakubovich. The *Laboratory of Theoretical Cybernetics* was founded there by Yakubovich in 1959. During the first years the main research direction in the Laboratory was pattern recognition. Several new mathematical approaches to pattern recognition were proposed, a few extensions of the Rosenblatt's *perceptron theory* were developed Yakubovich [1963, 1965]. Further theoretical generalization of the perceptron concept motivated Yakubovich to develop the *method of recursive goal inequalities (RGI)* and the finitely converging algorithms of their solution Yakubovich [1965, 1966]. A number of application problems have been solved during the 1960s: recognition of the handwritings, aerophotos, extracting signals from noisy measurements, analysis of scenes, etc. The idea of the RGI method is close to the gradient search. However, the goal is formulated in terms of the inequalities, and the special choices of step sizes (gain sequence) of the algotithm are proposed. Under such a choice the algorithms provide solution of an infinite number of the inequalities which were not shown to the system after a finite number of steps. This is in a contrast with standard iterative methods for linear inequalities by Agmon, Motzkin and Shoenberg. Based on those results Yakubovich provided a general framework for solving adaptive control problems. Particularly, he introduced a first mathematical *definition of adaptive system* Yakubovich [1968]. In addition, in paper Yakubovich [1968] the concept of *robot* have for the first time appeared in Russian engineering literature.

The most active coworkers of Yakubovich were A.Kh.Gelig and V.N.Fomin. Fomin has published the book on the mathematical theory of pattern recognition systems Fomin [1976] and Gelig has published the monograph on stability of neural networks Gelig [1982]. Both books were the first in their areas in the Russian literature. The main results of the school in the area of adaptive control were summarized in the book Fomin *et al* [1981].

As a reader can see, the above mentioned attempts to deal with *adaptation* in broad sense had not a big coverage of *adaptive control* itself, they mostly related to estimation, identification, stochastic optimization, machine learning. However there were numerous researchers in the USSR, who worked in the framework of adaptive control in its precise sense and tried to apply it to real-life problems. We can mention such names as B.N.Petrov, V.Yu.Rutkovski, I.I.Perelman, A.G.Aleksandrov in Moscow; A.E. Barabanov, A.A.Pevozvanski, O.Yu. Kultchitski, V.E. Kheisin in Leningrad; Yu.I. Neimark, M.M.Kogan in Gorkii, Kuhtenko and Kuntcevich in Kiev; unfortunately we are unable to surwey their researches here in detail. Some basic references are Kogan & Neimark [1987], Kuntsevich & Lychak [1992], Pervozvanski [1992], Petrov et al [1980].

4. CONFERENCES AND SYMPOSIA

There was also activity in organization of conferences, workshops and other scientific meetings. Two series of meetings were most important in the area of adaptive control. The first one organized by a team guided by Ya.Tsypkin *School-seminar on adaptation* took place every two years. They were hosted by researchers in various scientific centers and republics of the USSR. Geography of the last meetings is impressive: Winter 1973 - Armenia, Summer 1974 - Lithuania, Summer 1976 - Georgia, Winter 1978 - Kazakhstan, Summer 1979 - boat trip along Enisey river, Siberia, Summer 1982 - Kyrgizia, Winter 1984 - Belorussia, Summer 1986 - Moscow region (this 13th School-seminar was the last one.) There were usually 50 to 100 attendees from main research centers of the whole country, including both professors and their students. The discussions with scientific leaders like Tsypkin, Yakubovich, A.Krasovskii, V.Rutkovsky, R.Yussupov, Yu. Neimark, etc. maintained a unique atmosphere of creativity and friendly knowledge exchange. Unfortunately only reports on the 7th, 9th and 13th schools were published Avedyan & Kelmans [1974], Avedyan *et al* [1979, 1987].

Another remarkable series of meetings, entitled *Leningrad symposia "Theory of adaptive systems"* was organised and chaired by Yakubovich in Leningrad in 1972, 1974, 1976, 1979. The number of attendees was usually from 300 to 400. As for the number of the talks at the 1st symposium 41 talks were presented, while 146 talks in 1974, 277 talks in 1976, 214 talks in 1979. In 1983 the 1st All-Union conference "Theory of adaptive systems and its application" was organised by the Leningrad branch of the IFAC USSR NMO headed by the corresponding member of Academy of Sciences A.A.Vavilov with 448 papers and more than 600 participants. One of the authors of the present talk served as the Secretary of all those meetings. More information about the program and the main talks of the symposia of 1974, 1976, 1979 can be found in the reports Derevitskii & Fradkov [1975], Derevitskii *et al* [1977], Fradkov & Yakubovich [1981]. The main talks of the 1st Symposium of 1972 are published in Adaptive Systems [1974]. The program and the main talks of the All-Union conference of 1983 are characterized in Fradkov [1984].

In addition to the above mentioned series of the meeting separate events were also organized devoted to some important areas related to adaptation, learning and robustness, e.g. Seminar on Dynamics Of Control-Systems And Processes in Gorkii (currently Nizhnij Novgorod) in 1974 Belyustina & Neimark [1974]and All-Union school-seminar on Sensitivity Theory of Control Systems and Its Applications in Vladivostok in 1975 Ermachenko & Yusupov [1976], etc.

5. ROBUSTNESS AND SENSITIVITY

Going back to the citation of Tsypkin, opening this paper: "Three characteristic periods can be distinguished in the development of the theory of automatic control. For convenience, they are briefly called the periods of determinism, stochasticism and adaptivity." Actually, one more period worth to be added — period of *robustness.* This approach also treats uncertainty, but from another point of view — it tries to find properties which can be guaranteed for all admissible uncertainties (e.g. robust stability or robust performance).

Related approach studies behavior of systems under small perturbations of parameters. Pioneering researches were done by Yugoslavian scientists — Kokotovic [1964], Tomovich & Vukobratovich [1972]. Created by them *sensitivity theory* was actively grabbed in the USSR; main advocates of the theory were scholars from Leningrad, see Rozenvasser & Yusupov [1969], Gorodetskiy *et al* [1971], Rozenvasser & Yusupov [1981]. They organised several All-Union conferences on sensitivity. Sometimes these were joint conferences on *sensitivity and invariance.* The history of invariance theory is worth mentioning. Before WW2 there was the publication Schipanov [1939] with novel approach to design. The goal was to synthesize control systems with invariant output, not depending on external perturbations. Formal conditions which imply such property were introduced. However neither effective tools to implement such controllers nor examples were presented. Moreover the last sentence in the paper writes: "All other controllers which do not satisfy above conditions should be declared to be unfit." The paper generated a wave of protests. There was a special resolution of the Academy of Sciences with disapproval of the publication; Institute of Automation and Remote Control was in real danger. However the war stopped the progress of the situation. Many years later more carefull analysis exhibited possibility of invariance property in some special cases, and more important, demonstrated design tools to decrease dependence on perturbations (but not to delete it). Thus several special conferences on invariance have been arranged.

But more realistic models of uncertainty treated not small but bounded perturbations. First problems of this sort arose in estimation and observation. *Unknown-but-bounded* models were suggested by Withenhausen, Schweppe, Bertsekas and others in 1960th. In Soviet Union this line of research was developed by N.N. Krasovsky school, see Kurzhanski [1977]. Special *ellipsoidal technique* Chernousko [1988] is based on the assumption that uncertainties lie in ellipsoids, and estimates of states and parameters are constructed via ellipsoids as well.

The next field of research is *robust stability* analysis, i.e. analysis of stability of systems with parametric or functional uncertainty. As we have mentioned above, the first direction here is called *absolute stability* and the first publication relates to 1944 Lur'e and Postnikov [1944]! In state-space notation problem formulation is as follows: given dynamical system

$$\dot{x} = Ax + b\phi(c^T x), \quad x, b, c \in R^n, \tag{4}$$

with scalar nonlinear monotone function $\phi(q)$ satisfying sector condition

$$\alpha q \leq \phi(q) \leq \beta q.$$

Is any such system stable provided that all linear systems

$$\dot{x} = Ax + \gamma b, \alpha \leq \gamma \leq \beta$$

are stable (*Aizerman conjecture*, 1948)? There are numerous results relating absolute stability, see e.g. Lur'e [1951], Aiizerman and Gantmakher [1963], and this field is still active in Russian literature.

Absolute stability theory dealt with nonlinear systems, but it was a surprise that there are unsolved problems for linear systems with uncertain parameter. The breakthrugh was the paper Kharitonov [1978], devoted to problem robust stability of characteristic polynomials. Consider the interval polynomial family

$$\mathcal{P} = \{P(s) = a_0 + a_1 s + \ldots + a_n s^n, \quad \underline{a}_i \leq a_i \leq \overline{a}_i,\} \tag{5}$$

and construct four *Kharitonov's polynomials*:

$$P_1(s) = \underline{a}_0 + \underline{a}_1 s + \overline{a}_2 s^2 + \ldots$$
$$P_2(s) = \underline{a}_0 + \overline{a}_1 s + \overline{a} s^2 + \ldots$$
$$P_3(s) = \overline{a}_0 + \overline{a}_1 s + \underline{a}_2 s^2 + \ldots$$
$$P_4(s) = \overline{a}_0 + \underline{a}_1 s + \underline{a} s^2 + \ldots$$

Kharitonov's theorem claims, that if these four polynomials are Hurwitz, then any polynomial of the interval family is Hurwitz. Thus robust stability of linear systems with uncertain coefficients of the characteristic polynomial can be easily checked. Later the graphical version of the result was provided in Tsypkin and Polyak [1991].

However numerous hopes on "bright future" of parametric robustness opening via Kharitonov's theorem failed. Neither problems with interval matrices, nor cases with nonlinear depedence of coefficients on parameters, nor discrete-time systems did not admit "Kharitonov-like" extensions. One way to overcome the difficulties relies on so called *D-partition*, introduced in Neimark [1948]. It is based on the analytical expression of the boundary of stability domain in the parameter space: a system leaves sability, when a root of the characteristic polynomial crosses the imaginary axis or the power of the polynomial decreases. The parameter space can be either uncertainty parameters or design parameters (e.g. coeffitients of PID controller). Unfortunately this approach is effective for low-dimensional spaces of parametrs only. For 2D case there is graphical description of the stability domain, but it is hard to extend it for larger dimensions. State-of-the-art in D-decomposition theory is presented in Gryazina et al [2008].

More universal (but also more conservative) approach to parametric robustness was pioneered by Leitmann and Barmish. It is based on the use of common quadratic

Lyapunov funtion for all possible uncertaintees. The notion of *Linear Matrix Inequalities* Boyd et al [1994] happened to be highly effective for robustness analysis and synthesis. A survey of Russian research in the field can be found in Polyak and Scherbakov [2002].

CONCLUSIONS

The level of the research activities in the area of adaptive and robust control in the Soviet Union in the 1960s-1970s was very high. This brief paper is dedicated to survey of the theoretical results. Some application related results are presented in the survey Voronov & Rutkovsky [1984]. An overview of the development of adaptive and intelligent control in the 1980s can be found in the special issue IJACSP Special Issue [1992].

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