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The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report deals with research results obtained at the Center for Mathematical System Theory, University of Florida, Gainesville, Florida 32611 in the field of mathematical system theory. Special emphasis was given to the following areas:

(1) Finite-dimensional linear system theory by algebraic methods: linear systems over a ring, algebraic methods in the study of feedback, polynomial methods for the study of linear systems, F mod G invariant subspaces.

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20. ABSTRACT (continued)

(2) Infinite-dimensional linear systems: realization theory of infinite-dimensional linear systems.

(3) Nonlinear system theory: basic properties of polynomial (discrete-time) systems and their realization theory.

(4) Identification problems in economics: study of econometric model building.

The present report is only a brief summary of findings, which are far too technical to be explained in a few pages. The results are being gradually published in the open literature. For details, refer to previous proposals and/or to the publications listed in the references.

The program is expected to continue, the bulk of effort now being devoted to nonlinear problems.

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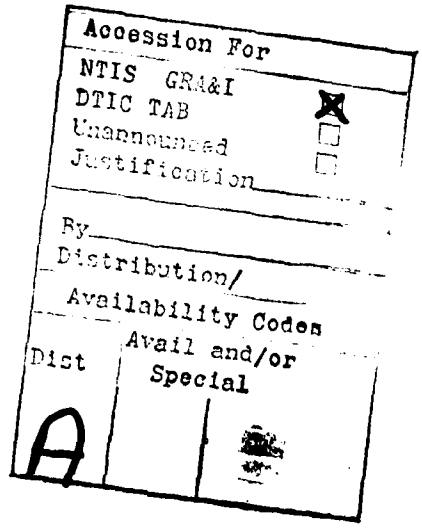

RESEARCH IN APPLIED MATHEMATICS RELATED TO NONLINEAR SYSTEM THEORY

Final Technical Report

September 1981

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CENTER FOR MATHEMATICAL SYSTEM THEORY
UNIVERSITY OF FLORIDA
GAINESVILLE, FL 32611

1. TECHNICAL BACKGROUND AND ACCOMPLISHMENTS

During many years in the past, funds from this grant were used primarily to support postdoctoral research at the Center for Mathematical System Theory at the University of Florida. During the period covered by this report, the following postdoctorals were involved:

E. EMRE (1977-1980, with interruption)

J. HAMMER (1980 to present)

Such support is limited to two years but is usually less.

In addition, several predoctoral students were also supported, albeit on a much lower financial level. This list includes F. HAMANO, P. KHARGONEKAR, J. RIBERA, Y. YAMAMOTO, and T. GEORGIOU. Also supported was the Principal Investigator (partial summer support only) and various short-term visitors (research "consultants") who lectured on their recent work directly relevant to Center research.

A complete list is given in Section 3.

a. Overview.

During the present four-year period of the grant, the number of publications were much larger than the number during the previous three-year period. (See Final Report, covering the period May 1, 1975 through April 18, 1977.)

This was not due to a large increase of personnel or the diligence of the individuals, but simply to the fact that publications are subject to a long lag. Moreover, in any serious research program, several years may be necessary before the problems become clearly defined but then the results come relatively quickly.

A number of external publications (for example, by ROUCHALEAU, HAZEWINKEL, FLIESS, and KAMEN) have been strongly influenced by the

Center. These are not included in the list in Section 3 which is limited to work that actually carried acknowledgement to the Army Grant to which this report pertains. Even a cursory look at the system-theoretic literature, however, will show that the influence of the Center research went far beyond the work summarized here.

b. Finite-dimensional linear system theory by algebraic methods.

This work constituted the bulk of the research. All members of the Center contributed in various ways, at least through internal discussions and seminars. The effort in this area may be subdivided as follows:

(i) Linear systems over a ring. This topic is concerned with the extension of linear methods to problems where these methods might at first not be expected to be relevant, namely to systems described by "numbers" belonging to an arbitrary (commutative) ring. This may be the ring of integers (where division is not possible) or more abstract quantities, such as polynomials, instead of ordinary numbers.

The fundamental publication, summarizing also earlier results, is ROUCHALEAU and SONTAG [1979]. A major survey article, SONTAG [1976a], was published relatively early, influencing many future publications outside the Center; within the Center, SONTAG [1976b], [1977], [1978a], KHARGONEKAR [1980], and KHARGONEKAR and SONTAG [1981] are the main publications, together with some papers which treat the concomitant mathematical issues such as DICKS and SONTAG [1978].

(ii) Algebraic methods for the study of linear systems. This topic began with a paper by KALMAN in 1965 which showed that linear system theory, especially as regards the method then called "Laplace transform", may be expressed elegantly and powerfully by the study of modules over polynomial rings.

This point of view was greatly extended by HAUTUS and HEYMANN during a joint visit at the Center in 1976, resulting in the major publication HAUTUS and HEYMANN [1978]. In this paper the algebraic machinery involving polynomial rings is extended to the study of various types of formal power series which are especially important in the analysis of feedback.

Partly in collaboration with HEYMANN these results were further generalized by HAMMER [1981a-e], who joined the Center in August 1980 as a research associate. This is a good example of research, which has begun at the Center, having influenced other groups (HEYMANN and HAMMER are both affiliated with the Technion in Israel). See also HAMMER and KHARGONEKAR [1981].

(iii) Polynomial methods for the study of linear systems. A large number of publications, especially by EMRE [1978, 1980a, 1980b] alone as well as in collaboration with members of the Center (see EMRE and HAMANO [1979], EMRE and HAUTUS [1979, 1980], EMRE and KHARGONEKAR [1980]) and also with outsiders (see EMRE and SILVERMAN [1979, 1980a-b]).

(iv) F mod G invariant subspaces. This topic belongs to the so-called geometric theory of control popularized in the early 1970's by WONHAM (Toronto). The object of research at the Center was to show that the cumbersome (and not very powerful) geometric methods of WONHAM can be improved by algebraizing the problem. This problem was studied especially by ANTOULAS (not supported by the ARO), culminating in a doctoral dissertation at the Swiss Federal Institute of Technology in 1979. Closely related to this are the publications EMRE and HAUTUS [1979, 1980], KHARGONEKAR and EMRE [1980].

A major "breakthrough" was achieved in KALMAN [1979] which showed that the problem of determining F mod G-invariant subspaces may be handled with methods of partial realization theory which, at

first sight, appear to be irrelevant. Recent research at the Center follows this direction but has not been completed as of the writing of this report.

(v) Infinite-dimensional linear systems. The main research effort in this area was the Ph.D. dissertation YAMAMOTO [1978] and subsequent publications based on this work and extending it (see YAMAMOTO [1980] and [1979]).

YAMAMOTO introduced the notion of "topological observability" which means that the initial state of a linear (infinite-dimensional) system may be determined by means of continuous operations on the output data generated by the system. He then showed that if a canonical realization is defined to be one which is quasi reachable and topologically observable then the celebrated uniqueness theorem holds also in the infinite-dimensional case. This clarifies certain difficulties apparent in earlier work by BROCKETT and FUHRMANN who claimed that such a uniqueness theorem cannot hold. YAMAMOTO has been able to show that the Brockett-Fuhrmann claimed "counterexample" is the result of certain technical mathematical misunderstandings. Having cleared up these misunderstandings, research can now proceed further in order to arrive at a workable definition of infinite-dimensional linear systems.

c. Nonlinear system theory.

This problem has been under very active discussion, internal seminar talks, etc. for several years. Research continues but at a relatively modest pace, due to the very great conceptual and technical difficulties involved.

The main work is represented by the Ph.D. dissertation of SONTAG [1978c]. With some additions, this work was subsequently published in book form as SONTAG [1979b]; it could be regarded as the first modern textbook in the application of algebraic-geometric techniques to system theory. The effort needed to study this book

is justified by the very important fact that the uniqueness theorem of canonical realization can be shown to be valid for arbitrary finite-nonlinear (that is, polynomial systems). The first statement and proof of this theorem appears in SONTAG and ROUCHALEAU [1976], and a complete treatment is given in SONTAG [1979b].

In certain special cases more complete results can be obtained, as in KALMAN [1979d]. See also the short survey paper KALMAN [1978].

The investigation begun by SONTAG in connection with realization theory was extended by himself in several directions, especially in regard to the characterization of observers for nonlinear systems. See SONTAG [1978b, 1979a, and 1979c].

A very important part of nonlinear system theory, based on classical invariant theory in pure mathematics, is the determination of invariants of quadratic optimization problems related to the Riccati equation. This topic has been discussed for a long time at the Center and finally solved by KHARGONEKAR in a forthcoming doctoral dissertation (finished after the period covered by this report). This work has quite direct practical implications and is one of the major topics to be emphasized in 1981/1982.

d. Identification problems in economics.

This area of work grew out from the general interest in practical identification problems related to the theoretical investigations supported under this and previous grants.

It turns out that there are serious misunderstandings in economics and econometrics---involving incompletely understood system-theoretic questions---concerning the nature of "identification" interpreted as building mathematical models from economic data. The first publications related to the above "discovery" are KALMAN [1979a, 1979e, 1980, 1982].

This field is under active study; important mathematical results were obtained after the preparatory papers quoted above. These papers are not yet complete as of the date of this report.

e. Reprintings.

This is an interesting illustration of the importance of research supported under predecessors of the present ARO Grant or earlier.

Examples are:

KALMAN [1977a], a paper originally published in 1963.

KALMAN [1979f], a paper originally published in 1964.

KALMAN [1979d], an English translation of a paper written in 1968 but previously published only in Russian.

KALMAN [1979b] is a so-called "citation classic" concerned with a paper published in 1962.

f. General.

The papers published under the grant are generally available from the Center for Mathematical System Theory, without charge as a matter of professional courtesy. However, in view of the high cost of reprints and mailing at the present time, we would prefer not to distribute large quantities of these papers to general ARO mailing lists.

2. PUBLICATIONS AND REFERENCES

a. Publications carrying grant acknowledgements (or relevant to final report)

W. DICKS and E. D. SONTAG

[1978] "Sylvester domains", Journal of Pure and Applied Algebra, 13: 243-275.

E. EMRE

[1978] "On algebraic equivalence of the formulation of observers" (to appear).

[1980a] "On a natural realization of matrix fraction descriptions", IEEE Transactions on Automatic Control, AC-25: 288-289.

[1980b] "The polynomial equation $QQ_c + RP_c = \Phi$ with applications to dynamic feedback", SIAM Journal on Control and Optimization, 18: 611-620.

E. EMRE and F. HAMANO

[1979] "Exact model matching to state-feedback" (to appear).

E. EMRE and M. L. J. HAUTUS

[1979] "Polynomial characterization of (F, G)-invariant and reachability subspaces", Proceedings of the 18th IEEE Conference on Decision and Control, pages 7-10.

[1980] "A polynomial characterization of (A, B)-invariant and reachability subspaces", SIAM Journal on Control and Optimization, 18: 420-436.

E. EMRE and P. P. KHARGONEKAR

[1980] "Regulation of split linear systems over rings: coefficient assignment and observers", to appear in IEEE Transactions on Automatic Control.

E. EMRE and L. M. SILVERMAN

[1980a] "K-observers for linear systems with unknown inputs", IEEE Transactions on Automatic Control, AC-25: 779-782.

[1980b] "Partial model matching of linear systems", IEEE Transactions on Automatic Control, AC-25: 280-281.

[1979] "The equation $XR + QY = \Phi$: a characterization of solutions", SIAM Journal on Control and Optimization, 19: 33-38.

J. HAMMER

[1981a] "Linear dynamic output feedback: invariants and stability" (submitted for publication in IEEE Transactions on Automatic Control).

[1981b] "On causality, inverses and feedback", Second International Symposium on Dynamic Systems, University of Florida.

[1981c] "On internally stable linear control", Proceedings of 1981 International Symposium on the Mathematical Theory of Networks and Systems, Santa Monica, CA.

[1981d] "On some properties of conditional moments in nonlinear filtering", to appear in SIAM Journal on Control and Optimization.

[1981e] "Stability and stable precompensation: an algebraic approach" (submitted for publication SIAM Journal on Control and Optimization).

J. HAMMER and P. P. KHARGONEKAR

[1981] "Decoupling of linear systems by dynamic output feedback" (submitted for publication in IEEE Transactions on Automatic Control).

M. L. J. HAUTUS and M. HEYMANN

[1978] "Linear feedback: an algebraic approach", SIAM Journal on Control and Optimization, 16: 83-104.

M. L. J. HAUTUS, M. HEYMANN, and R. J. STERN

[1977] "Rest point theorems for autonomous control systems", Journal of Mathematical Analysis and Applications, 58: 98-112.

R. E. KALMAN

[1976] "Realization theory of linear dynamical systems", in CONTROL THEORY AND FUNCTIONAL ANALYSIS, Vol. II, International Automatic Energy Agency, Vienna, 1976, pages 235-256.

[1977a] "Lyapunov functions for the problem of Lur'e in automatic control", reprinted in NONLINEAR SYSTEMS: STABILITY ANALYSIS, edited by J. K. Aggarwal and M. Vidyasagar, Dowden, Hutchinson, and Ross, pages 201-205.

[1977b] "A new approach to linear filtering and prediction problems", reprinted in LINEAR LEAST SQUARES ESTIMATION, edited by T. Kailath, Dowden, Hutchinson, and Ross, pages 254-264.

[1978] "Nonlinear realization theory", held at University of Virginia, Charlottesville, VA, in Transactions of the Twenty-Fourth Conference of Army Mathematicians, US Army Research Office, Triangle Park, NC, pages 259-269.

[1979a] "A system-theoretic critique of dynamic economic models", in GLOBAL AND LARGE-SCALE SYSTEM MODELS, edited by B. Lazarević, Springer, pages 1-24.

[1979b] "Contributions of the theory of optimal control", author's reflective comments on article published as "citation classic" in Current Comments, PC & ES, No. 32, page 14.

[1979c] "On partial realizations, transfer functions, and canonical forms", Acta Polytechnica Scandinavica, Mathematics and Computer Science Series No. 31, pages 9-32.

[1979d] "Pattern recognition properties of multilinear response functions, I-II", Control and Cybernetics, 8: 331-361. (English translation of paper previously published only in Russian.)

R. E. KALMAN

[1979e] "Theory of modeling", Proceedings of the IBM System Science Symposium, Oiso, JAPAN, October 1979, pages 53-69.

[1979f] "When is a linear control system optimal?", reprinted in FREQUENCY RESPONSE METHODS, edited by A. J. C. MacFarlane, IEEE Press, pages 71-80.

[1980] "System theoretic critique of dynamic economic models", International J. of Policy Analysis and Information Systems, 4: 3-22.

[1981] "Mathematical system theory: the new queen?", Texas Tech University, Mathematics Series No. 13, in AMERICAN MATHEMATICAL HERITAGE: ALGEBRA AND APPLIED MATHEMATICS, pages 121-127.

[1982] "Identifiability and problems of model selection in econometrics", to appear in ADVANCES IN ECONOMIC THEORY, Vol. 2, Cambridge University Press.

P. P. KHARGONEKAR

[1980] "On matrix fraction representations for linear systems over commutative rings", to appear in SIAM Journal on Control and Optimization.

P. P. KHARGONEKAR and E. EMRE

[1980] "Further results on polynomial characterizations of (F, G)-invariant subspaces", to appear in IEEE Transactions on Automatic Control.

P. P. KHARGONEKAR and E. D. SONTAG

[1981] "On the relation between stable matrix fraction factorizations and regulable realizations of linear systems over rings", to appear in IEEE Transactions on Automatic Control.

P. P. KHARGONEKAR, T. T. GEORGIOU, and A. B. OZGULER

[1981] "Skew-prime polynomial matrices and invariant subspaces", Proceedings of 1981 International Symposium on the Mathematical Theory of Networks and Systems, Santa Monica, CA.

Y. ROUCHALEAU and E. D. SONTAG

[1979] "On the existence of minimal realizations of linear dynamical systems over noetherian integral domains", Journal of Computer and System Sciences, 18: 65-75.

E. D. SONTAG

[1976a] "Linear systems over commutative rings: a survey", Richerche di Automatica, 1: 1-34.

[1976b] "On linear systems and noncommutative rings", Mathematical Systems Theory, 9: 327-344.

[1977] "The lattice of minimal realizations of response maps over rings", Mathematical Systems Theory, 11: 169-175.

[1978a] "On finitary linear systems", presented at the International Federation of Automatic Control Conference, Helsinki, August 1978.

[1978b] "On first-order equations for multidimensional filters", IEEE Transactions on Acoustics, Speech, and Signal Processing, ASSP-26: 480-482.

[1978c] "Realization of polynomial response maps", Ph.D. dissertation, Department of Mathematics, University of Florida.

[1979a] "On the observability of polynomial systems, I: Finite-time problems", SIAM Journal on Control and Optimization, 17: 139-151.

[1979b] POLYNOMIAL RESPONSE MAPS, Lecture Notes in Control and Information Sciences, No. 13, Springer, New York, 168 pages.

[1979c] "Realization theory of discrete-time nonlinear systems: Part I - bounded case", IEEE Transactions on Circuits and Systems, CAS-26: 342-356.

E. D. SONTAG and Y. ROUCHALEAU

[1976] "On discrete-time polynomial systems", Nonlinear Analysis Theory, Methods and Applications, 1: 55-64.

Y. YAMAMOTO

[1977] "Topological observability and uniqueness of canonical realizations".

[1978] "Realization theory of infinite-dimensional linear systems", Ph.D. dissertation, Department of Mathematics, University of Florida.

[1979] "Realization theory of infinite-dimensional linear systems - Part I and Part II", to appear in Mathematical Systems Theory.

[1980] "Some remarks on the reachability of infinite-dimensional linear systems", Journal of Mathematical Analysis and Applications, 74: 568-577.

Note.

This list contains items which were written or submitted during the period of the present grant but which will be published only after the expiration of the grant.

3. PERSONNEL SUPPORTED UNDER THE GRANT

(a) Regular Personnel

Professor R. E. Kalman, Principal Investigator (partial summer support only).

Dr. E. Emre, postdoctoral research associate (now on faculty of Texas Tech. University).

Mr. T. Georgiou, doctoral student.

Dr. F. Hamano, doctoral student (now Florida Atlantic University).

Dr. J. Hammer, postdoctoral fellow (1980-1982).

Dr. P. P. Khargonekar, doctoral student (now on faculty of University of Florida).

Mr. J. Ribera, doctoral student.

Dr. E. D. Sontag, doctoral student, later postdoctoral fellow (now on faculty of Rutgers University).

Dr. Y. Yamamoto, doctoral student (now on faculty of Kyoto University, Kyoto, JAPAN).

(b) Visitors (several lectures and/or extended visits)

A. Antoulas, Swiss Federal Institute of Technology, Zurich, SWITZERLAND.

M. Arbib, University of Massachusetts.

E. Arthurs, Bell Telephone Laboratories.

G. Basile, University of Bologna, Bologna, ITALY (now on faculty of University of Florida).

C. Byrnes, Harvard University.

F. Clement, Ecole Centrale, Paris, FRANCE.

E. J. Davison, Toronto University, CANADA.

M. Ershov, University of Linz, AUSTRIA.

M. L. J. Hautus, Technological University of Eindhoven, NETHERLANDS.

M. Hazewinkel, Rotterdam Econometric University, NETHERLANDS.

M. Heymann, Technion, Haifa, ISRAEL.

G. Marro, Computer Center and Automation, Bologna, ITALY.

T. Matsuo, Nagoya University, JAPAN.

Y. Rouchaleau, Ecole des Mines, Antibes, FRANCE.

E. Kamen, Georgia Institute of Technology (now on faculty of University of Florida).

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