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19. ABSTRACT (Continue on reverse if necessary and identify by block number) A brief overview and summary of the research carried out in the area of approximation theory and computational methods for the identification and control of distributed parameter systems is provided. In particular, this final report details our efforts during the period 1 November, 1990-31 October, 1993 on projects involving the adaptive control and estimation, and on-line identification of distributed parameter systems (including a collaborative experimental effort with Air Force personnel at Phillips Laboratory at Edwards Air Force Base), the identification and control of degenerate distributed parameter systems, Multi-grid methods for the solution of optimal LQR control problems for infinite dimensional systems, wavelet based approximation in the optimal LQ control of distributed parameter systems, the identification of nonlinear Volterra equations with application to materials with memory, the LQ control of linear and nonlinear distributed parameter systems with infinite spatial domain, and optimal control and estimation of thermoelastic systems with applications to thermo-acoustic refrigeration.

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Final Report for Approximation Theory and Computational Methods for the Identification and Control of Distributed Parameter Systems

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1. Adaptive Control and Estimation and On-Line Identification of Distributed Parameter Systems: A significant portion of our research effort was concentrated in this area. We have been investigating a discrete time indirect adaptive linear quadratic control scheme (and associated finite dimensional approximation theory) for distributed parameter systems. The scheme we have been looking at requires an on-line, real time parameter identifier to provide parameter updates to the LQ control design procedure. The largest portion of our effort to date on this project has been put into the development of an on-line parameter identifier. This work has been a collaborative effort with Professor Petros Ioannou of the Department of Electrical Engineering - Systems at USC and our joint student, Mr. Michael Demetriou. Mr. Demetriou received the Ph.D. degree in Electrical Engineering from USC in August 1993, and accepted a post-doctoral research appointment at the Center for Research in Scientific Computing (CRSC) at North Carolina State University which commenced in September of 1993.

The approach we have taken is well known to researchers in the area of finite dimensional adaptive control (in particular, there are a number of papers in this area by Narendra and his co-workers) and has been investigated in the case of second order elliptic (i.e. static) partial differential equations. We are of course interested in evolution equations. The approach involves the construction of an infinite dimensional system of evolution equations, the state of which consists of a state estimator and an estimate of the unknown parameters (whether they be scalar or vector constants or functions). The system is constructed in such a way that a Lyapunov like argument yields convergence to both the true state of the system and the actual parameters as time tends to infinity. The key result that we have obtained is a sufficient condition for convergence of the parameters. This condition, which is an observability- or coercivity-like condition, is that the plant be what is known as *persistently excited* or sufficiently rich. This condition also guarantees identifiability. It is a direct extension of the analogous result in finite dimensions.

We have developed the theory for both first (abstract parabolic) and second (abstract hyperbolic) order partial differential equations, and thus our approach can handle a number of important applications. In particular, it is applicable to the identification of a variety of dissipation or damping mechanisms, including thermoelasticity, in flexible structures. We have also developed an associated finite dimensional approximation theory and have obtained corresponding convergence results. To date we have tested our scheme on the identification of a number of constant and functional (i.e. spatially varying) parameters in regular and degenerate heat and wave equations (using simulated plants) and have found it to perform exceedingly well. The analysis of these schemes and its testing was the subject of Mr. Demetriou's Ph.D. thesis which was written under the joint direction of Professors Ioannou and Rosen, and which was successfully defended in April of 1993.

We have made a number of trips to the Phillips Laboratory at Edwards Air Force Base. In collaboration with Phillips Laboratory staff members Dr. Alok Das, Dr. Joel Berg, and Mr. Keith Denoyer, we have designed an experiment that will allow us to test our scheme. The experiment consists of a flexible (aluminum) beam clamped at one end and cantilevered at the other. Excitation can be introduced via a piezo-electric patch near the root, and displacement data is collected via a number of proximity sensors mounted along a bracket alongside of the beam. We intend to attempt to use our schemes to identify the known stiffness parameter (for the purpose of proof of concept) and a number of unknown dissipation or damping parameters, and then compare our results with a number of off-line techniques. The first step in our study was to construct a simulation of the experiment. This has been done. Next we intend to use the simulation to tune and test our scheme. This phase is currently underway. Once this has been completed, we will then use data generated by the experiment and collected on disk to simulate on-line identification off-line. Finally, we will attempt to carry out the identification on-line. We expect to continue this aspect of investigation as a part of the new and continuing research program that we have proposed to AFOSR. We also intend to continue our collaboration with the researchers at the Air Force's Phillips Laboratory.

In the fall of 1993 we have started to develop a *one space theory* for Lyapunov-based adaptive identification schemes. The approach we have used in developing schemes has depended heavily upon a Gelfand triple formulation of both the plant and the estimator. A one space theory should prove to be significantly more versatile and should be able to be applied to a much larger class of plants and estimators. In particular, this would include hereditary, or delay, systems, and finite dimensional estimators for infinite dimensional systems. We have been considering the application of our theory to both linear and nonlinear plants. We have also started to look at a Lyapunov-based model reference adaptive control (MRAC) scheme for both linear and nonlinear plants. In this case the resulting error equations which must be analyzed are nonlinear. We do this via the theory of monotone operators and nonlinear semigroup theory. We have established the convergence of the tracking error to zero, the boundedness of the feedback controller, and if a particular persistence of excitation or richness condition is satisfied by the reference model, then parameter convergence is achieved. We have tested our scheme via numerical simulation on parabolic (both linear and nonlinear), hyperbolic, and hereditary systems. Our first papers on the topics discussed in this paragraph should be completed by the end of the year.

Our first major papers in this area were completed in the Fall of 1992. Several additional papers were completed throughout the final year of the grant. They are listed below, and re-prints and pre-prints have been included for your inspection. A number of conference papers have also been completed and are listed below as well. We have spoken on these results as an invited speaker at the Conference on Problems in Sensing Identification and Control of Flexible Structures at the Fields Institute for Research in Mathematical Sciences at the University of Waterloo, Waterloo, Ontario, Canada, in June of 1992, at the SIAM Conference on Control and its Applications in Minneapolis in September of 1992, at the University of California, Santa Barbara in October of 1992, at the IEEE Conference on Decision and Control (CDC) in December, 1992, as an invited speaker at the Evolution Equations Conference held at the Louisiana State University in January of 1993, at the IEEE Conference on Aerospace Control in May of 1993, and at the 1993 American Control Conference in June (where it won the Best Paper in Session award). We were also invited to speak on these results at Humboldt-Universitat-Berlin in Berlin, Germany and at the International Conference on the Control and Identification of Distributed Parameter Systems in Vorau, Austria, during the Summer of 1993. We have also given invited seminar talks on this research at the University of Michigan (Department of Aerospace Engineering) and at Michigan State University (Department of Mathematics) in October of 1993.

2. Multi-Grid Methods for the Solution of Linear Quadratic Regulator Problems for Infinite Dimensional Systems: We have looked at the introduction of multi-grid, or more appropriately, multi-level techniques into the numerical solution of the in general, high order finite dimensional matrix algebraic Riccati equations which result when LQ control problems for distributed parameter systems are discretized. Our goal in this research was to accelerate convergence, improve accuracy, and reduce computation time. As our past experience has shown us, in particular with the thermoelastic problems that we have looked at, these are extremely important considerations in the solution of infinite dimensional regulator problems and must be addressed. Our approach was based upon the iterative Newton-Kleinman method for solving the algebraic Riccati equation, and Smith's method for solving the resulting matrix Lyapunov equations. We have made use of the fact that the operator equations we are trying to solve have come from an optimal control problem and in particular involve the shifting of eigenvalues of the open-loop semigroup generator. We have some theoretical results which help in understanding why the technique yields an improvement over existing non-multi-grid techniques, and we have carried out numerical studies on simple test examples involving a one dimensional heat equation. This is joint work with Professor Chunming Wang of the Department of Mathematics at USC. A paper reporting our findings has been accepted for publication in the SIAM Journal on Numerical Analysis. A pre-print has been included for your inspection.

3. Wavelet Based Approximation in the Optimal Linear Quadratic Control of Distributed Parameter Systems: We have developed wavelet based Galerkin approximation schemes for the closed loop solution of optimal linear quadratic regulator problems for distributed parameter systems. Wavelets constitute a recently discovered family of complete orthonormal systems of recursively computable functions. They possess time/frequency localization and regularity properties that make them attractive candidates for use as trial functions in finite element approximation. They are especially useful in the resolution of singular or near singular behavior. Our investigation involved both convergence analysis (with regard to the approximating solutions to the algebraic Riccati equation and optimal feedback gains) and numerical studies. For the latter we considered two examples, the control of a one dimensional heat/diffussion equation and vibration damping in a visco-thermoelastic rod. Our conclusion was that wavelet approximation proved to be competitive with other generic approximation methodologies, such as spline based or spectral methods, and offers certain distinct advantages over existing techniques by virtue of the unique properties of wavelet transforms. This research was joint work with Dr. Chris Brislawn, currently a post-doctoral fellow at the Los Alamos National Laboratory, who was a visitor in the Air Force supported Center for Applied Mathematical Sciences in the Department of Mathematics at USC during the months September thru November of 1990. Our findings have been reported on in the paper *Wavelet based approximation in the optimal control of distributed parameter systems*, which appeared in Numerical Functional Analysis and Optimization, Volume 12, 1991, pp. 33-78. A re-print of this paper has been included for your inspection. These results were discussed in a seminar at the Center for Nonlinear Studies at Los Alamos National Laboratory, and in a seminar at the Interdisciplinary Center for Applied Mathematics at the Virginia Polytechnic Institute and State University. Our results were also presented in a talk in an invited session at the SIAM Annual Meeting in Chicago in July of 1990.

4. Identification of Nonlinear Volterra Equations: We have extended our abstract approximation results for the identification of nonlinear infinite dimensional evolution systems to the identification of systems described by nonlinear Volterra integral equations. We first considered general Volterra equations of the form

$$x(t) + \int_0^t b(t-s)Ax(s)ds \ni F(t), \qquad 0 \le t \le T,$$

where $x(t) \in X$ with X a Banach space, $b : [0,T] \to R$, $F : [0,T] \to X$, and $A : D(A) \subset X \to X$ a nonlinear, possibly set valued, m-accretive operator on X. We defined an associated initial value problem and the notion of a mild solution, and then we established an abstract approximation result in the spirit of the Trotter-Kato Theorem. We then specialized to the case of Hilbert space and Gelfand triples, and the operator A being strongly monotone and maximal. We defined an associated inverse problem and developed a rather general approximation and convergence theory. Finally, we applied our general theory to a well known model for nonlinear heat conduction in materials with memory.

This work was joint with Professor S. Aizicovici of the Department of Mathematics at Ohio University in Athens, Ohio, and Professor Simeon Reich of the Department of Mathematics at USC. Our results were reported on in the paper *An approximation theory for the identification of nonlinear Volterra equations*, which will appear in Numerical Functional Analysis and Optimization, in the Summer of 1993. A re-print has been included for your inspection.

5. The Identification and Control of Degenerate Distributed Parameter Systems: We have developed an abstract approximation framework for the identification of nonlinear degenerate distributed parameter systems. By a degenerate system we mean one in which the operator coefficient of the term involving the highest order derivative is non-coercive and as such does not admit a bounded inverse. This type of system occurs frequently in applications. In particular, these applications include models for heat conduction and fluid mechanics, diffusion through porous media, and wave propagation. This effort represents an extension of our earlier treatment of linear degenerate distributed parameter systems. We consider problems in which the leading (or "generalized mass") operator is linear, symmetric and non-negative and the "generalized stiffness" operator is maximal monotone. Our approach required that we establish a version of the well-known nonlinear Trotter-Kato approximation results for nonlinear evolution systems (for example, the results by Crandall and Pazy and Goldstein) which is applicable to either regular or degenerate implicit systems. The resolvent convergence condition is replaced by a similar one involving right inverses. Numerical studies were carried out on the Cray at the NSF supercomputing center in San Diego. This effort was joint with my student Chao Lin Mao (and was the topic of his doctoral dissertation which was completed and defended in the Summer of 1991), and Professor Simeon Reich of the Department of Mathematics at USC, an expert in the area of nonlinear functional analysis and evolution equations. A paper detailing both our theoretical results and numerical findings has been accepted for publication in the Journal on Nonlinear Analysis. A pre-print has been included for your inspection.

We have now turned our attention to the development of an abstract approximation framework for the identification of both linear and nonlinear second order degenerate distributed parameter systems. We are considering problems in which the leading (or "generalized mass") operator is linear, symmetric and non-negative, the "generalized stiffness" operator is linear symmetric and coercive, and the damping operator is monotone. This effort is joint with my student Poornima Raghu (and will be the topic of her doctoral dissertation), and Professor Simeon Reich.

We are also currently investigating the application of our approximation theory for degenerate systems in the context of linear-quadratic control for certain classes of infinite dimensional descriptor variable systems. To date, we have been looking at the development of a theoretical framework for the LQ control problem when the state is governed by a degenerate system of abstract parabolic type. We hope to be able to characterize the optimal control law in linear state feedback form in terms of degenerate state and co-state equations leading to appropriate Riccati like operator equations. We expect our treatment to parallel the well established finite dimensional theory that has been reported on in a recent paper of Alan Laub's. We then intend to develop a corresponding finite dimensional approximation theory which addresses both convergence questions and computational issues. We expect that the algorithms developed by Laub for the optimal LQ control of finite dimensional descriptor systems will be appropriate for the solution of the finite dimensional approximating control problems. Numerical studies are currently underway and have resulted in several open questions. In particular, we have started to look at mixed finite element methods in an effort to address some of the difficulties which have arisen in the solution of the approximating LQ control problems.

We have started to look at the application of the techniques that we have, and are, developing for degenerate systems in the context of the thermal blooming problem for laser beam propagation in the atmosphere. The beam, propagating in an absorbing fluid, heats the medium and thus alters the fluid's density and therefore its refractive index. The change in the refractive index defocuses the beam resulting in decreased intensity at the target. The equations describing this process consist of a wave equation describing the beam's propagation, nonlinearly coupled to a diffusion-like equation describing the dynamics of the refractive index of the medium. When linearized, a system of the general form

$$\frac{\partial u}{\partial t} + v \cdot \nabla u = -2\Gamma F + \alpha \Delta u,$$

$$\frac{1}{2k}\Delta\phi + \frac{\partial F}{\partial z} = 0,$$

$$\frac{1}{2k}\Delta F - \frac{\partial \phi}{\partial z} + ku = 0,$$

results, where k is the wavenumber for the beam, and F, ϕ, and u are the perturbations in the field intensity, field phase, and fluid dielectric constant, respectively. The constant α is the fluid's thermal diffusivity, v is the mean transverse velocity of the fluid, and Γ is a linearization constant related to the fluid's thermal response. Note that the system above consists of coupled parabolic and elliptic equations. Consequently, we feel that it may be treated as a degenerate (or, in the finite dimensional nomenclature, a descriptor variable) system. At present we are looking at the well-posedness of both the nonlinear and linearized systems. We are considering abstract formulations as well as one dimensional analogs in order to facilitate understanding. It is our goal to be able to apply the identification, control and approximation theory that we have been, and are developing for degenerate systems to inverse and control problems associated with these systems and equations. Our study is in its early stages, and we expect to continue our investigation as part of the research program described in the pending proposal which we have submitted to AFOSR.

6. Other Projects: We have a Ph.D. student starting to look at the control of nonlinear conservation laws in the context of flow control. The approach we are taking involves the design of an LQ feedback controller based upon a linearized model. This control law will then be used to close the loop on the nonlinear system and the resulting performance will be monitored. Our investigation will involve both analysis and numerical simulation. Of particular interest to us in this context are systems that are most appropriately modeled on an infinite spatial domain with the perturbation to the equilibrium operating state that is to be driven to zero, the action of the input actuator, and the data collected by the sensor being relatively local in nature. It is our intention to attempt to take advantage of the local nature of these disturbances, input, and output, and develop wavelet based approximation schemes for control design. By taking advantage of the local resolution properties of wavelet bases, we expect that reasonably good approximations to the optimal control law can be obtained using a relatively low dimensional approximation. Our previous experience with wavelet based approximation in the context of control design for distributed parameter systems (as was described earlier in this section) should be of some value to us as our effort in this area progresses. At present, it is in its early stages and is serving as the topic for a student's (Mr. Il Jin Park) doctoral research.

Finally, we have also started to look at identification and control problems related to thermoacoustic refrigeration and vibration. Thermoacoustic refrigeration is a process by which sound energy is used to move heat up a temperature gradient. Thermoacoustic vibration is the reverse process whereby a mechanical vibration is induced by a thermal input source. The technolgy can then be used to design refrigerators and heat pumps, which because of their relatively few moving parts (in fact the only moving part is the speaker diaphragm) have great potential for space applications. They also reduce the risk of ozone layer depletion due to chloroflourocarbon (CFC) pollution. Our investigation has led us to consider the introduction of unbounded input (i.e. boundary control) and unbounded output (i.e. boundary measurement) into the theory we developed earlier for the optimal LQG control of linear thermoelastic systems. This research effort is serving as the doctoral thesis topic for my student, Mr. Kamal Hamdan. At present, Mr. Hamdan has established a number of theoretical results and is beginning to carry out numerical studies. We hope to continue the efforts discussed in this final sub-section as a part of the research effort that we have proposed to AFOSR.

7. Research Papers Produced under AFOSR Grant No. AFOSR-91-0076:

1. On Stabilizability and Sampling for Infinite Dimensional Systems (with C. Wang), *IEEE Transactions on Automatic Control*, Vol. 37, 1992, pp. 1653-1656.

2. Wavelet Approximation in the Optimal Linear Quadratic Control of Distributed Parameter Systems (with C. Brislawn), *Numerical Functional Analysis and Optimization*, Volume 12, 1991, pp. 33-77.

3. Approximation in the Identification of Nonlinear Degenerate Distributed Parameter Systems (with C. Mao and S. Reich), *Journal on Nonlinear Analysis*, Theory, Methods, and Applications, to appear.

4. A Multi-level Technique for the Solution of the Linear Quadratic Regulator Problem for Distributed Parameter Systems (with C. Wang), *SIAM Journal on Numerical Analysis*, to appear.

5. An Approximation Theory for the Identification of Nonlinear Volterra Equations (with S. Aizicovici and S. Reich), *Numerical Functional Analysis and Optimization*, Volume 14, 1993, pp. 213-227.

6. An On-Line Parameter Estimation Scheme for Flexible Structures (with M. Demetriou), Proceedings of Workshop on Problems in Sensing, Identification and Control of Flexible Structures, Fields Institute, Waterloo, Ontario, Canada, June 28-30, 1992, J. E. Marsden, Editor, American Mathematical Society, Providence, R.I. 1993.

7. Adaptive Identification of Second Order Distributed Parameter Systems (with M. Demetriou), *Inverse Problems*, to appear.

8. Adaptive Parameter Estimation for a Class of Distributed Parameter Systems with Persistence of Excitation (with P. Ioannou and M. Demetriou), Proceedings of 31st IEEE Conference on Decision and Control, Tucson, Arizona, December 16-18, 1992, pp. 1742-1743.

9. On Persistence of Excitation in the Adaptive Estimation of Distributed Parameter Systems (with M. Demetriou), Proceedings 1993 American Control Conference, San Francisco, California, June 2-4, 1993, pp. 454-458.

10. On Persistence of Excitation in the Adaptive Estimation of Distributed Parameter Systems (with M. Demetriou), *IEEE Transactions on Automatic Control*, to appear.

11. On-Line Parameter Estimation for Infinite Dimensional Dynamical Systems (with M. Demetriou), *SIAM Journal on Control and Optimization*, in revision.

12. Dynamic Identification for Implicit Parabolic Systems (with M. Demetriou), Proceedings of Conference on Evolution Equations, Louisiana State University, Baton Rouge, Louisiana, January 7-11, 1993, submitted.

13. Adaptive Paramater Estimation for Degenerate Parabolic Systems (with M. Demetriou), *Journal of Mathematical Analysis and Applications*, submitted.

14. Adaptive Estimation of a Flexible Beam (with M. Demetriou), Proceedings of IEEE Regional Conference on Aerospace Control Systems, Thousand Oaks, California, May 25-27, 1993, pp. 815-819.

15. Adaptive Parameter Estimation for a Class of Delay Equations with Persistence of Excitation (with J. Kazimir), Proceedings of 32nd IEEE Conference on Decision and Control, San Antonio, TX, December 15-17, 1993, to appear.

16. Model Reference Adaptive Control of Abstract Hyperbolic Distributed Parameter Systems (with M. Demetriou), Proceedings of 32nd IEEE Conference on Decision and Control, San Antonio, TX, December 15-17, 1993, to appear.

17. Model Reference Adaptive Control of Abstract Nonlinear Distributed Parameter Systems (with M. Demetriou and S. Reich), Proceedings of 1994 American Control Conference, Baltimore, MD. , submitted.

18. Adaptive Identification of Nonlinear Distributed Parameter Systems (with J. Kazimir), Proceedings of Conference on Control and Estimation of Distributed Parameter Systems: Nonlinear Phenomena, Vorau, Austria, July 18-24, 1993, submitted.

19. Model Reference Adaptive Control of Infinite Dimensional Dynamical Systems (with M. Demetriou and S. Reich), in preparation.

8. Ph.D. Students Supported under AFOSR Grant No. AFOSR-91-0076 and their Project Titles:

1991	C. Mao	An Approximation Theory for the Identification of Nonlinear Degenerate Distributed Parameter Systems.
1993	M. Demetriou	Adaptive Parameter Estimation for Abstract Parabolic and Hyperbolic Distributed Parameter Systems. (Currently Research Assistant Professor, Center for Research in Scientific Computation (CRSC) North Carolina State University Raleigh, North Carolina.)
	K. Hamdan	Boundary Control of Thermoelastic Systems.
	J. Kazimir	Adaptive Identification of Distributed Parameter Systems.
	I. Park	Optimal LQ Control of Parabolic Systems with Infinite Spatial Domain.
	P. Raghu	Identification of Second Order Degenerate Distributed Parameter Systems.

9. U.S. Air Force Personnel Contacted under AFOSR Grant No. AFOSR-91-0076

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