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We report on several research projects funded by grant AFOSR-91-0021. Substantial progress has been made in statistical areas, especially in Bayesian analysis and empirical distributions, and in analysis of inverse problems in structures and groundwater modeling. Our numerical studies have focused on parallel statistical computing in inverse problems, identification in conservation laws, cooling of viscoelastic films, and a general problem involving the estimation of measures. We have computing facilities and the structures lab of Phillips Lab, in order to tailor the statistical and numerical techniques under study to those problems of interest to AFOSR. We have also visited AFESC at Tyndall AFB to discuss mathematical issues in groundwater modeling problems of interest to the Air Force.

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Final Technical Report: AFOSR-91-0021

Statistical and Numerical Methods in Control and Identification

Ben G. Fitzpatrick

We report here on several research projects funded by grant AFOSR-91-0021. Substantial progress has been made in statistical areas, especially in Bayesian analysis and empirical distributions, and in analysis of inverse problems in structures and groundwater modeling. Our numerical studies have focused on parallel statistical computing in inverse problems, identification in conservation laws, cooling of viscoelastic films, and a general problem involving the estimation of measures. We have visited computing facilities and the structures lab of Philips Lab, in order to tailor the statistical and numerical techniques under study to those problems of interest to AFOSR. We have also visited AFESC at Tyndall AFB to discuss mathematical issues in groundwater modeling problems of interest to the Air Force.

Bayesian Methods in Identification and Control. Bayesian analysis seeks to answer statistical questions using probability measures on the parameter space, measures which represent our uncertainty in the knowledge of the parameter. Inference begins with a prior probability measure on the parameter space, and through Bayes' theorem one calculates the conditional law of the parameter, given observations of the system (the posterior distribution).

The estimation problem can be tackled through Bayesian maximum likelihood, in which the posterior probability density is maximized. Of course, in many cases of interest, the parameter space is infinite-dimensional, and one must ask whether a density exists. We have handled this point by examining the similarities between Bayesian maximum likelihood and regularized least squares. One theoretical result of interest is that standard

H^1 Sobolev regularization corresponds to a prior distribution which is Wiener measure. Also, we have derived a convergence result which allows one to use densities in finite dimensional approximation spaces; the maximizers of the posterior densities can be shown to converge to minimizers of a regularized least squares cost functional. One advantage to the statistical approach is that regularization levels can be set with proven statitsical tools. We have studied the E-M algorithm within this context, and in future studies we shall examine the generalized cross-validation approach, which does not involve integration over the parameter space.

The hypothesis testing problem is also under study. The classical asymptotic approach, using ANOVA-like tests, suffers from several difficulties. In particular, it is necessarily restricted to finite-dimensional parameter spaces, with no available results on convergence for infinite dimensional situations. Furthermore, in cases in which a large amount of data is taken, common in structure experiments, the tests are too powerful, rejecting hypotheses when they are "close" to being correct. Bayesian tests allow an investigator to take such considerations directly into account in the inference procedure. Some numerical test examples are providing insight into how these tests work.

Empirical Distributions. Another approach to statistical inference in least squares identification is that of estimation of the error distribution. One first calculates the least sqaures estimator, and then uses the residuals as estimators of the observation error. By putting a mass of $1/n$ at each of these residual values, we create an empirical distribution for the estimated errors. Working with George Yin of Wayne State University, we have shown that as the sample size increases, this empirical distribution converges to the distribution of the observation errors, and that (properly scaled) the empirical distributions are asymptotically Gaussian. One can use this empirical ditribution in a Monte Carlo setting, called bootstrapping, by sampling from it and using the generated samples for inference.

A major advantage of bootstrapping is the inherent parallelism in the algorithm. One generates several simulated datasets based on the least squares estimate and residuals, and the simulated datasets in turn proved an empirical distribution of parameter values. The parallelism is in the generation of the simulated data. We have implemented this algorithm, for an example problem involving material parameters of an Euler-Bernoulli beam, on the 128 processor Intel iPSC/860 hypercube at ORNL. To implement this algorithm on a "standard" desktop workstation would require nearly a week of CPU time, while using 64 processors of the hypercube we could run the program in a few hours. We feel that this type of statistical technique holds great promise as a method that can provide valuable insight into problems of fitting models to data, and availability of efficient computational algorithms makes bootstrapping an attractive alternative to linearization and other approximations.

Optimal Cooling of Viscoelastic Films. A problem of interest in material science is the cooling of viscoelastic films in such a way that residual stresses are minimized. Together with Jack Weitsman and Kyun Lee of the Engineering Science and Mechanics Department of the University of Tennessee, we have proposed and analyzed algorithms for computing optimal temperature profiles. The stress is modeled using a nonlinear integral equation, which we solve with a combination of quadrature and Runga-Kutta techniques. Using compactness arguments we have derived convergence results for the stress and temperature approximations. Much of the computational work has been carried out by Azmy Ackleh, a graduate student in the UT Mathematics Department, and Jennifer Wright, an undergraduate who was participating in an NSF-sponsored "Research Experiences for Undergraduates" program.

Identification in Conservation Laws. In this project we examined the problem of determining parameters in conservation laws from observations of the system. Convergence ideas for monotone finite difference schemes have been extended to the identification problem, yielding results for convergence of parameter estimates in approximation in least squares. In order to obtain more accurate shock location, we have also implemented a third-order essentially nonoscillatory schemes. There are several applications of these ideas to forebody simulation and nozzle design in aircraft design problems. Also, these ideas may be very important in the analysis of contaminant transport in groundwater. Conservation laws are typically used to model chemical elution in liquid chromatography, a process which seeks to identify chemicals as they flow through a packed column. Chromatographic experiments are often used to determine adsorption rates of chemicals onto various types of soil. Also, developing remediation strategies based on volatilizing contaminants and collecting the vapor will require conservation law models. Strategies of this sort are currently being planned at Brooks AFB.

Approximation of Measures. When using Bayesian methods in infinite dimensional estimation problems, one must necessarily be concerned with finite dimensional approximation. We have previously studied the problem of approximating probability measures (and, more generally, vector *valued measures*) for some structured population models. Now we are focusing on probability measures for modeling uncertainty in material parameters. In large flexible truss structures, a variety of problems can arise due to slight differences in the material parameters of components. Vibration in engines due to turbine blade "mistuning" is another area in which probabilistic descriptions of parameter spaces are needed. We have developed some convergence theorems for computing dynamic response based on approximation of the underlying probability measure. Computations for such problems are highly parallelizable, and we are currently developing computational schemes for such problems.

Control Design with Uncertain Parameters. In cases such as mentioned in the previous paragraph, as well as in the simpler problem of controlling vibrations in a composite beams, material parameter values are not known exactly. Identification techniques can provide estimates, but control systems can be very sensitive to errors in such estimates. In particular, we have shown with a very simple example that inaccurately estimated damping in a damped linear oscillator can yield an LQR based control design that actually slows down the exponential decay rate of the uncontrolled system. The goal of this project is to devise control strategies based on probabilistic parameter information, that is, on a distribution on the parameter set. Working with H. T. Banks of North Carolina State University, we have proposed a quadratic cost functional, which resembles an expectation of the system over the parameter set. The linear regulator techniques can be extended to handle this new cost, and we are currently investigating numerical approximations. The extension makes heavy use of the abstract Hilbert space LQR theory developed (with strong AFOSR support) over the past 10-15 years. Computational evidence suggests that this technique will be better at maintaining stability margins than an LQR control based on inexact parameter estimates.

One of the difficulties with the above-mentioned approach is that the control obtained is not a feedback control for the original problem. While it is a feedback control in the extended problem, observations made of the original system cannot readily be extended for application of the feedback operator. To include system measurements into the control strategy, we have developed some adaptation schemes for tuning the parameter probabilities, based on measurement information and conditional probability. The scheme adjusts the probabilities, and hence the control, as more measurements are taken. Recent numerical results indicate that in certain cases these probability measures will concentrate at the true parameter as the number of measurements increase, and our theoretical investigations of this scheme are still underway.

Contaminant Transport in Groundwater. We are currently investigating mathematical models for the transport of contaminants in groundwater. We have made two trips to Tyndall AFB to discuss these problems with AFESC scientists. Major difficulties in modeling contaminant transport involve the heterogeneity of the medium, appropriate boundary conditions, and biological degradation. We are currently developing computational algorithms for contaminant transport simulation, using both spectral/ domain decomposition techniques as well as traditional finite element methods. We have applied the theoretical framework of Banks and Ito to study convergence in the parameter estimation problem. Subtleties in the analysis arise due to the need for discontinuous coefficients in the transport equation.

We are also investigating the use of statistical information about the medium in dynamic models and predictions. Our current effort is focused on kriging, which is a commonly used estimation/interpolation technique for determining hydraulic conductivity as a function, from discrete data.

Homogenization Methods in Truss Structure Modeling. In joint work with D. A. Rebnord of Syracuse University, we have developed a homogenization approach to the study of vibration of large truss structures. This work has focused on homogenization of the von Karman equations for large deflections. The type of results obtained involve finding an approximating (von Karman) equation system whose solution is on a simple domain. The results obtained require rather small external forces on the system; however, recent results of Simo indicate that this is exactly when the von Karman equation is a reasonble approximation to the 3-d elasticity equations. In further work we will investigate nonlinear membrane and inextensional theories, which are more accurate 2-d models of plate vibration for larger external forces.

Shape Design and Control for Smart Materials. In this project we are studying the use of piezoceramic actuators for bending a flexible body in order to match a desired shape. Applications for this work include bending flexible airfoils to achieve a specified shape as well as adjusting airfoils to the flow conditions. We have begun this project by examining the shape matching problem for a 1-d Euler-Bernoulli beam. The unboundedness of the input operator associated with piezoceramic actuators (two derivatives of a step function – the control appears as an induced bending moment) requires that the problem be formulated in the dual of the energy space. Moreover, some particular shapes may not be attainable with a given configuration of actuators. We have posed the problem as a minimum norm problem, and we developed existence and approximation results for finding control inputs. We are currently implementing our computational strategy. Further studies will involve optimal actuator placement to provide sufficiently accurate shape matching.

Summary and Forecast. We have made substantial progress in several areas of proposed research, many of which have indicated further directions of study. We have visited Philips Lab at Kirtland AFB and the AFCESA Lab at Tyndall AFB during the grant period, in an effort to develop a collaboration with Lab personnel. We have also traveled to the structures lab at Edwards, and we are beginning to implement the topics mentioned above in the context of experiments at the Lab.

Papers. The following is a list of papers completed during the term of the current research grant.

1. "Almost Sure Convergence in Distributed Parameter Identification Algorithms under Correlated Noise," by G. Yin and Ben G. Fitzpatrick, *Appl. Math. Letters,* **5**, no. 4, 1992, pp. 41-44.

2. "Bayesian Analysis in Inverse Problems," by Ben G. Fitzpatrick, *Inverse Problems*, **7**, no 5, October 1991, pp. 675-702.

3. "Approximation and Control in Integral Equations of Nonlinear Vicsoelasticity," by Ben G. Fitzpatrick, *J. Math. Systems, Estimation, and Control,* **2**, no. 4, 1992, pp. 483-501.

4. "Numerical Methods for Optimal Investment-Consumption Models," by B. G. Fitz-

patrick and W. H. Fleming, *Proc. 29th IEEE Conference on Decision and Control,* 1990, Volume 4, pp. 2358-2361.

5. "Invariance Principles and Applications to Distributed Parameter Identification," by G. Yin and B. G. Fitzpatrick, *Proc. 29th IEEE Conference on Decision and Control,* 1990, Volume 6, pp. 3556-3557.

6. "Modeling and Estimation Problems for Structured Heterogeneous Populations," by Ben G. Fitzpatrick, *J. Math. Anal. Appl.*, **172**, no. 1, 1993, pp. 73-91.

7. "Parameter Estimation in Conservation Laws," by Ben G. Fitzpatrick, *J. Math. Systems, Estimation, and Control,* to appear.

8. "Sample Distributions of Identification Algorithms for Distributed Parameter Systems," by G. Yin and Ben G. Fitzpatrick, *Proceedings of the 1991 International Symposium on the Mathematical Theory of Networks and Systems,* Mita Press, Tokyo, 1992, pp. 569-574.

9. "A Fourth Order Scheme for Nonlinear Integral Equations of Viscoelasticity," by Ben G. Fitzpatrick and J. W. Gebbie, *Appl. Math. Letters*, **5**, no. 3, 1992, pp. 63-67.

10. "On Invariance Principles for Distributed Parameter Identification Algorithms," by G. Yin and Ben G. Fitzpatrick, *Informatica*, Volume 3, no. 1, 1992, pp. 98-118.

11. "Inverse Dynamics Paradigm: Adaptive Nonlinear Control and Identification of Large-Scale Power Systems," by R. C. Berkan, B. R. Upadhyaya, R. A. Kisner, and B. Fitzpatrick, *Control-Theory and Advanced Technology*, Volume 8, no 3, 1992, 465-477.

12. "Empirical Distributions in Least Squares Estimation for Distributed Parameter Systems," by Ben G. Fitzpatrick and G. Yin,*J. Math. Systems, Estimation, and Control,* to appear.

13. "Statistical Tests of Fit in Estimation Problems for Structured Population Modeling,"

by Ben G. Fitzpatrick, *Q. Appl. Math.*, to appear.

14. "Homogenization of Von Karman Plate Equations," by Ben G. Fitzpatrick and D. A. Rebnord, *Proc. 31st IEEE CDC,*, Tucson, AZ, Dec. 16–18, 1992, 1160-1163.

15. "Bootstrap Methods for Inference in Least Squares Identification Problems," by Ben G. Fitzpatrick and G. Yin, to appear.

16. "The Linear Regulator Problem for Systems with a Distribution of Parameters," by M. Aczon, H. T. Banks, and Ben G. Fitzpatrick, *Proc. 31st IEEE CDC,* , Tucson, AZ, Dec. 16–18, 1992, 1168-1171.