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9.0 BRIEF OUTLINE OF RESEARCH FINDINGS

9.1 Overview of Accomplishments

In late 1986, when the Center for Intelligent Control Systems (CICS) was formed, we set out to investigate a core of subjects that might constitute the foundations of intelligent systems. We recognized that it would be essential to go beyond the standard paradigms of control theory and signal processing which deal with well-defined models of systems (using difference or differential equations), and that it would be necessary to investigate new models of uncertainty (going beyond stochastic processes) so as to be able to cope with uncertainty at different levels of granularity. We also recognized that the new constructs would need to deal with the structural representation of models at different levels of abstraction and that these representations should help facilitate the mathematical codification of the concepts of learning, adaptation and organization.

In this section we describe some of our research and educational accomplishments.

Research on Perceptual Systems

Understanding natural perceptual systems such as the human visual and auditory systems, and the synthesis of artificial perceptual systems, are important problems in the study of intelligent systems. Of course understanding naturally occurring perceptual systems has proven to be more difficult than anyone expected 50 years ago, and it now seems that it will require inputs from such diverse fields as brain and cognitive science, linguistics, and psychology, as well as mathematics (geometry, partial differential equations, random fields), systems, and computer science.

One possible view of the visual cortex is a computational one: it can be modeled as an information processing system consisting of several modules operating at different levels. The goal of the first step in vision (early vision) is to solve problems such as:

(i) segmenting an image into its natural regions
(ii) finding boundaries and detecting objects
(iii) organizing local information into a global structural description.

The integration of these computations is a challenging problem. Moreover, sensed images will invariably contain noise and hence these tasks will have to be performed in a robust way. Higher level processes may include:

(iv) the use of structural ideas to find more robust texture features
(v) the use of effective combinatorial descriptions of shape suitable for recognition in the presence of nonlinear distortions.

As a result of our research over the last few years, we now know how to attack some of these problems using ideas from the calculus of variations, geometric measure theory, and Markov random fields. This has lead to a deeper understanding of these problems.

Increasingly, however, we recognize that a separation into early vision and higher level problems may not provide the greatest insight. We believe that a central problem in vision is that of representing data at different levels (scales) and, indeed, that recognition is nothing else but representation at the correct level. These ideas are being tested from a variety of viewpoints. For example, we are using probabilistic ideas which take geometry into account, so as to understand how one synthesizes an ideal image from noisy data.

The line between perception and understanding is not at all sharp. We know from Kanisza's work that the idea of perception is extremely complex. A computational theory which explains our perception of Kanisza's illusory figures is itself a challenging problem, but preliminary studies suggest that mathematics can be useful.

On a more pragmatic level, the problem of aided or automatic target recognition (ATR) is ubiquitous and still not adequately solved. Continuing progress on the ATR problem relies on new advances in mathematical approaches to image analysis, object representation and recognition, and decision theory.

A promising attack on the high-level problem of recognition of shapes has been launched. It is based on:

(i) creating deformable templates to represent idealized objects.
(ii) developing a methodology (drawn from statistics and sequential decision theory) for the recognition of rigid objects which may present themselves in a variety of aspects and forms due to rotations, partial obscuration, or sensor noise.

Surprisingly, some reasonably advanced mathematical ideas involving infinite-dimensional stochastic differential equations and infinite-dimensional manifolds have played a role here.

Research on perceptual systems at the CICS has been led by Professors Brockett, Geman, Gidas, Grenander, Maragos, McClure, Mitter, Mumford, Willsky, and Yuille. Details of their work may be found in their individual reports in Section 9.2.

Multiscale Signal and Image Analysis

The investigation of multiscale representations of signals and the development of multiscale algorithms is a topic of considerable current interest. One of the more recent areas of investigation in multi-scale analysis resulted in the development of a theory of multiscale signal representations and wavelet transforms, and it has frequently been suggested that it should be possible to develop efficient optimal processing algorithms based on these representations. The development of such algorithms requires the development of a corresponding theory of stochastic processes and their estimation. Work in this area has had this as its objective.

We have taken some initial steps towards developing a theory for multiresolution stochastic processes, and a corresponding signal processing and estimation methodology. The wavelet transform leads naturally to the investigation of stochastic processes on dyadic trees and a more general class of weighted lattices in which different depths in the tree or lattice correspond to different scales, thereby exposing the "time-like" nature of the scale index and allowing us to begin the development of scale-to-scale recursive specification of multiscale stochastic processes. In particular, in our initial work we have focused on processes on dyadic trees. We have also introduced a class of linear state space models evolving "causally in scale" (i.e. from coarse to fine) on the dyadic tree. We have shown how the statistics of such a process can be evaluated efficiently, and we also develop a generalization of Kalman Filtering and smoothing for such models. These algorithms have some interesting twists. For example, the Kalman fine-to-coarse recursion involves not only the prediction and measurement update steps familiar from standard Kalman Filtering but also a new *fusion* step arising in the estimation of a coarse-level signal description based on estimates at fine levels. This leads to a new class of multiscale Riccati equations whose analysis requires a corresponding system theory. We have provided some initial steps in developing this system theory and in performing analysis of the Riccati equations. We also have introduced two other algorithmic structures. One involves the use of the Haar transform to transform the estimation problem into a set of decoupled (and much simpler) problems at different scales. The second algorithmic structure is iterative in nature and, in fact, has exactly the structure of popular and highly efficient multigrid algorithms.

Another part of our research on multiscale processes on dyadic trees has had as its aim the development of a theory for modeling what might be described as multiscale autoregressive (AR) processes -- i.e. AR models evolving in scale. In this work we develop a generalization of lattice structures and the celebrated Levinson and Schur recursion of time series analysis. Again, thanks to the tree structure of the index set, we find that there are significant and extremely important differences between our theory and the standard time series case. In particular our lattice structures involve prediction error vectors that increase in dimension as the order of the structure increases. This is due to the fact that the number of points on the tree that are a specified distance or "lag" away from a given point increases as the lag increases. Also, the reflection coefficients defining such a model satisfy different recursions and are subject to different constraints, due to the fact that there are more stringent constraints on a correlation sequence for a multiscale process on a tree than on such a sequence for an ordinary stationary time series. From our analysis it appears that multiscale AR models may be as useful a model class of multiscale signal processing as standard AR models are for so many problems in more classical signal processing contexts.

Research on multiscale signal and image analysis at the CICS has been led by Professor Willsky. Details of this work may be found in his individual report in Section 9.2.

Intelligent Control

Over the last few decades, developments in control theory have established a sound foundation for designing linear control systems, and a suitable language for specifying performance requirements in the areas of stochastic control, system identification and even stabilization of unknown, but linear, systems. Aspects of this theory have been extended so as to include important classes of smooth nonlinear systems. These developments do not, however, directly address a number of the most important issues one faces in designing or analyzing systems which are intelligent in the sense that they can exhibit the flexible strategies and/or opportunistic behavior required for dealing with large grained uncertainty. In the field of motion control -- e.g. autonomous vehicles, robotics, and smart machine tools, as well as modern chemical process control and some types of manufacturing systems -- traditional methods must be augmented with techniques that allow the system to exhibit a great capacity for learning about its environment, making a strategical analysis, and reacting appropriately. It seems likely that recent developments in statistics and the continuing work on probabilistic approaches to learning will have substantial impact on the resolution of these questions.

Instead of describing the input to such a system in terms of a vector of set points, or in terms of a class of trajectories to be tracked, it is often more suitable to think of the inputs as being a symbol string describing a sequence of moves or strategies that the system is to execute. In this sense systems of interest in intelligent control are sometimes described as symbol-to-signal transducers. Although the techniques for describing the structure and specifying the performance of such systems are still under development, tools for relating automata-like models and differential equation models are now emerging from developments in nonlinear system theory. These dynamical systems methods give a unified framework for studying interesting broad classes of intelligent systems.

By their very nature, intelligent systems often consist of interconnected modules distributed in space. Because the feedback control of interconnected systems requires coordination, it is necessary for the system to make efficient use of the available communication resources, and this includes deciding what information is useful enough to share. Moreover, because feedback control of a localized system may involve complex decision making (e.g. path planning) in order to facilitate the decision making processes, it is often necessary to abstract from the totality the data available in order to reduce the description of the problem to manageable proportions. In both cases one is faced with feedback loops in which substantial data reduction is essential. If this reduction can be described in terms of finding an approximation relative to some metric, then we may think of it as quantization. On the other hand, if the situation is such that "high level" abstractions are involved, then new methods, possibly derived from a combination of control and information theory will be required. Such methods are now being explored by workers in natural perception using mathematical techniques such as template matching. The application of these ideas to real-time control problems seems appropriate.

A broad range of applications are built on the foundation of the basic research in intelligent systems. Indeed, the concept of a machine that can process sensory information, make optimal decisions based on the sensory inputs and well-defined objectives, and translate those decisions into actions, is a guiding and unifying theme for basic research in all three directions: control, perceptual systems, and communications and computation. The technological challenge, for example, of implementing a control and communication system for a remote tele-operated vehicle over a low bandwidth communication channel is not simply addressed with methods already available. The effective design of such a system stimulates and, in turn, benefits from new mathematical formulations and analysis of problems in communication theory computer vision, and control.

Research on intelligent control at the CICS has been led by Professors Brockett, Ho, Kushner and Mitter. Details of their work may be found in their individual reports in Section 9.2.

Research on Learning

Learning research at CICS in the last few years has been primarily theoretical rather than empirical in character. Our aim was to develop the fundamental principles and techniques for learning by machines. Artificial intelligence (AI) research in learning has been typically characterized as empirical in nature, with little attention paid to the generality and scalability of the techniques. In contrast, our theoretical research is very much concerned with the efficient use of resources (both computational time and data are the resources considered), and with the breadth of applicability (trying to learn as generally as possible).

A very important part of our work is the development and exploration of various formal models for learning. The "distribution-free" or "PAC" model (originally proposed by Valiant) has been one of our most successful models, and has inspired much research. In this model of concept learning, it is assumed that there is an unknown probability distribution governing the generation of both training and test examples; this represents the "natural" distribution the learner faces. The learner must come up with a hypothesis that correctly classifies an example drawn randomly from this distribution with high probability, using a reasonable (polynomial) number of examples and a reasonable (polynomial) computation time.

Another direction of research that we have pursued is the understanding by machines of simple environments. We may wish to build a robot that, when placed in such an environment, can build up a model of its environment by experimentation and exploration. (It may have a variety of primitive operations available that characterize its interface to its environment, such as walking, manipulating, etc.) We have investigated what can be done with deterministic, finite-state environments, and have developed powerful new techniques for learning such environments.

Another question we have pursued concerns the fundamental limitations of learning -- what can we say about what can not be learned efficiently? Such research helped to clarify the boundary between what is efficiently learnable and what is not efficiently learnable in a given model; giving guidance as to when the learning algorithms may need additional assumptions or tools. For example, the ability to actively experiment with an environment gives the learning algorithm greater power than merely being able to passively observe. Similarly, certain kinds of concepts may be efficiently learnable if the underlying probability distribution is known to be of a certain type, but not if the distribution is arbitrary.

We have also investigated the effect of noisy data on learnability. In many cases, it can be shown that if a certain class of concepts is learnable in the noise-free case, then a certain amount of noise in the data can be tolerated as well, without interfering with learnability. Quantifying the amount of noise that can be tolerated is a significant theme in our research. There are other themes to our research that reflect concerns common to AI as well, such as the effect of the knowledge representation techniques on learnability. Here, however, our concerns typically reflect the impact of representation on computational efficiency, whereas a typical AI approach would be concerned with representational expressive power alone.

Other concerns that we address are more statistical in nature, reflecting the fact that learning is a gradual process where knowledge is accumulated over many examples, and that the amount of data required to learn depends both on the quality of the data and on the prior knowledge available about the unknown concept or phenomenon. A related statistical issue we have investigated relates the quality of "fit" of a hypothesis to the data versus the "complexity" of the hypothesis; this is a fundamental trade-off in many real-life applications.

The theoretical work in machine learning has already had an impact on practice, in that empirical researchers will now try to assess the adequacy of their data bases for the kinds of conclusions they are drawing, by comparing the theoretical bounds on the amount of required data with the amount available.

Our work on exploration of environments is fundamental research directed towards applications such as autonomous robots exploring unknown environments. While our research makes assumptions (such as the finite-state assumption) that may be unrealistic in practice, we are looking to relax as many of these assumptions as we can, to match theoretical work with real applications.

We expect that a number of the learning algorithms that we have developed for theoretical purposes are likely to be of some practical utility. For example, one of our learning algorithms based on the use of Fourier transforms in boolean domains has inspired some researchers to apply these techniques in practice, with good results.

Our studies of the effect of noise on learnability may have utility in applications, since real-life data is rarely "clean."

Research on learning at the CICS has been led by Professors Mitter, Rivest, and Valiant. Details of their work may be found in their individual reports in Section 9.2.

Control of Linear and Nonlinear Systems

A primary objective of the research in the Center is to capture in a quantitative and precise way the fundamental limitations of controller design in the presence of uncertainty and to provide a consistent methodology for design. The uncertain environment, as well as the design specifications, should reflect realistic and practical situations. In that regard, we have developed a new methodology, now known as the l_1 design methodology, for designing robust controllers in the presence of bounded, persistent, but unknown disturbances. This theory has received considerable attention by the control community, in both academia and industry, for its practical significance and computational advantages. The l_1 theory parallels in spirit the H_∞ theory. However, it differs in the sense that it is the only theory that allows time domain specifications in the presence of unknown, bounded disturbances.

The computation of l_1 optimal solutions involves solutions of semi-infinite linear programs. In this respect, we have developed methods for approximating these problems by utilizing the specific structure of these LPs. The approximation is in the form of lower and upper approximations of the problem that converge to the exact value in the limit.

A crucial development of the l_1 theory was in the area of robust stability. There, it was shown that conditions on the l_1 norm of the systems transfer function provide tests for stability robustness in the presence of plant perturbations. These conditions were shown to be non-conservative, and can be optimized using the l_1 theory to maximize the stability margin.

The robust performance problem in the presence of structured perturbations can be solved by satisfying conditions in terms of a scaled l_1 norm. We have shown that these conditions are related to the spectral radius of certain matrices that capture the structure information. Using these ideas, we hope to develop software by which one can synthesize controllers that deliver robust performance. Also, we are developing software utilizing Matlab, that will allow us to test the methodology on practical problems. Preliminary work has been done applying these ideas to the X-29 aircraft.

Another area of research concerns infinite-dimensional systems. Most systems are, in reality, infinite-dimensional, i.e. governed by partial differential equations. Examples of such systems are delay systems. This motivated us to develop a theory that allows designing controllers for infinite-dimensional systems using finite dimensional techniques. This was done by approximating the plant in specific frequency ranges (usually compact sets) by a finite-dimensional plant. A robust controller is then designed based on this finite dimensional plant. This design has to be done in a very specific way, since otherwise the resulting controller may not even be a stabilizing controller. We have shown that we can design H_∞ controllers that deliver a performance within a small deviation from the best achievable performance. This provided a readily computable method for obtaining H_∞ sub-optimal controllers for infinite-dimensional plants. In addition, exact solutions for the l_1 and H_∞ problems in the presence of delays (commensurate) have been furnished.

Motivated by the many applications of multirate controllers, we have studied the problem of multirate systems in the context of robust control. In the case of synchronous sampling, we have provided computable solutions for the l_1 robust performance problem. We have shown that the solutions for this problem are no harder to obtain than are those of the standard l_1 problem. The linear programs are in general of higher dimension. In the H_∞ context, we have shown that the solution of this problem can be obtained by a convex, finite dimensional programming problem which is readily computable.

In the case of asynchronous sampling, we have done preliminary studies showing that such systems can be approximated by a sequence of slowly varying synchronous systems. This problem is still under consideration.

We have developed a methodology based on linear theory for designing robust controllers for slowly-time-varying systems, in which the dimension of the system is not known to be fixed. The development is input/output and has immediate applications to adaptive control. The reason is that in adaptive control, the estimator provides estimates that form a slowly-time varying system, to which a controller is designed. We have shown that the closed loop performance can be directly related to the frozen-time performance of the system and hence, providing constructive methods for designing adaptive controllers that achieve a certain degree of stability robustness.

A basic problem in robust control theory is recognizing whether one needs adaptive time varying controllers in a specific design problem. For this purpose, we have studied the advantages gained in using time-varying controllers for the disturbance rejection and robust stabilization problems in the presence of bounded inputs. We have shown that time-varying controllers offer no advantages in these two problems in the case where the plant is linear time-invariant. Similarly for nonlinear smooth controllers. The problem is still open when the uncertainty is structured in nature.

Research on the control of linear and nonlinear systems at the CICS has been led by Professors Brockett, Dahleh, Fleming, Kushner, Mitter, and Verghese. Details of their work may be found in their individual reports in Section 9.2.

Computation

It is often said that parallel computation offers the best hope for solving very large problems. However, there is increasing awareness that making this hope a reality is very challenging, even for problems with naturally parallelizable structure. Specialized processor arrays can be very effective for some highly regular problems but often cannot cope efficiently with the sparsity structures that characterize many large numerical problems. In shared memory machines the number of processors is limited to a few tens, so the potential for large speedup and large problem solution is also limited. In massively parallel message-passing machines (e.g. hypercube-like architectures with thousands of processors), a principal bottleneck is the communication cost. In particular, solving large numerical problems in reasonable time requires fine grain parallelization and an accordingly large number of message exchanges between processors. Furthermore, when using iterative methods, there is a substantial penalty for synchronizing a large number of processors at each iteration.

To alleviate the communication bottleneck in message-passing systems, it is important to develop better communication algorithms, and to understand the nature and impact of communication and synchronization delays.

Working along these lines, we have been conducting research in two broad areas:

(i) development of optimal routing algorithms for generic communication problems in hypercube and other architectures;

(ii) quantifying the advantages and limitations of asynchronous algorithmic implementations that may avoid the synchronization penalty inherent in synchronous iterative methods.

There are a number of generic communication problems that arise frequently when using iterative and other algorithms in message-passing machines. For example, we may want to send a message from each processor to every other processor. This problem, called *multinode broadcast*, arises in linear iterations of the form $x := Ax + b$. If we assume that there is a different processor updating each coordinate of x, and that the matrix A is dense, then at the end of an iteration, there is a need for every processor to send the updated value of its coordinate to every other processor.

Algorithms for solving the multinode broadcast and other related communication problems have recently been developed for several popular architectures. These algorithms execute in time that grows at the optimal rate with the number of processors, and are often optimal in that they terminate in the minimum possible number of time steps. The underlying assumption here is that each message requires unit time for transmission on any link of the processor network, and that each processor can transmit and receive a message simultaneously on all of its incident links.

Current research is directed towards relaxing these assumptions and towards developing optimal algorithms for a variety of additional communication problems. This work also tries to evaluate the impact of communication on the solution of large problems. For example, it is simple to show that by using a hypercube network of processors and optimal communication algorithms, most of the basic operations of numerical linear algebra -- i.e. inner product, matrix-vector multiplication, matrix-matrix multiplication, power of a matrix, etc. -- can be executed in parallel in the same order of time as when communication is instantaneous. In some cases this is also possible when the processors are connected with a less powerful network such as a square mesh.

In asynchronous implementation of parallel iterative algorithms, processors are not required to wait to receive all messages generated during the previous iteration. Rather, each processor is allowed to keep iterating on its own component at its own pace. If the current value of the component updated by some other processor is not available, then some outdated value received at some past time is used instead. Furthermore, processors are not required to communicate their results after each iteration but only once in a while. Thus, some processors may compute faster and execute more iterations than others, some processors may communicate more frequently than others, and the communication delays may be substantial and unpredictable.

The potential advantages from asynchronous execution are implementation flexibility, and convergence acceleration due to a reduction of the synchronization penalty. Indeed, recent experimental work as well as theoretical analysis have shown that for important classes of problems, asynchronous implementations lead to substantial gains in speed of convergence over their synchronous counterparts. A drawback of asynchronous iterations is that they may diverge for some problems where their synchronous counterparts are guaranteed to converge. Nevertheless, a large number of interesting and mathematically challenging results have been developed showing that certain classes of important algorithms retain their desirable convergence properties in the face of asynchronism.

In the area of simulated annealing, we have made several major contributions. The paper by Tsitsiklis may well be the definitive paper on simulated annealing for finite state spaces. The paper by Gelfand and Mitter is the first analysis of simulated annealing in unbounded domains and continuous state space. The papers by Holley-Stroock and Diaconis-Stroock give interesting connections between the spectral gap and optimal cooling rates in simulated annealing.

Another area of research concerns continuous computation. Although many of the classical algorithms involving descent can be interpreted as using the integral curves of differential equations to guide the flow of the successive approximations, the digital implementation of such algorithms usually seeks to replace the continuous descent algorithms with one which involves large (discrete) step sizes. This usually leads to faster convergence. On the other hand, it has been reported in the literature that when using descent methods for function minimization it is better to use continuous descent if the function is so complicated that it can not be well approximated by a quadratic. Moreover, as the technology associated with analog VLSI grows more mature, direct analog simulation is becoming feasible in more cases.

Several researchers in the Center have pursued ideas along these lines. On one hand we now know that arbitrary automata can be realized by assigning the states of the automata to equilibrium points of a forced differential equation $x' = f(x,u)$ and that we can always take f to be quadratic in x. We have also shown that a variety of techniques from linear algebra can be generated by flows on the space of matrices. Eigenvalues, singular values, eigenspaces, etc. can be generated in this way. In his thesis, Faybusovich has undertaken a systematic study of linear programming from this point of view. This work also makes contact with the literature on training neural networks and the problem of learning principal components.

Research on computation at the CICS has been led by Professors Bertsekas, Cleighton, Goldwasser, Micali, Strang, and Tsitsiklis. Details of their work may be found in their individual reports in Section 9.2.

Research on Communication and Distributed Computation

It is widely recognized that it is technologically difficult and operationally ill-advised to build complex systems that cover large geographical areas, and are controlled in a centralized way. Because of this, distributed control systems have become increasingly important, and the corresponding distributed algorithms have been the subject of intensive study. At the same time there has been continuing research on communication networks that use distributed algorithms and also form an integral part of distributed intelligent systems.

Research on communication networks is relevant to intelligent systems in three important ways. First, distributed intelligent systems contain networked communication as an essential ingredient, and the performance of the system depends critically on the performance of the network. Second, and more important, the control of a communication network is a problem in which classical control is inadequate and an approach more like that being developed for intelligent control is required. Third, and perhaps most important, understanding the problems of distributed estimation, and distributed recovery from error events is critical to establishing conceptual foundations for the intelligent control of large distributed systems. These problems appear in a particularly pure and unencumbered form in the study of networks. A variety of distributed communication issues are now being investigated such as failure recovery, distributed routing, flow control, and broadband multiaccess communication. With communication speeds increasing by orders of magnitude in the near future, the conceptual framework for addressing these issues is likely to evolve considerably.

Research on communication and distributed computation at the CICS has been led by Professors Bertsekas, Gallager, Humblet, and Tsitsiklis. Details of their work may be found in their individual reports in Section 9.2.

9.2 Researchers' Reports

Dimitri Bertsekas

The work led by Professor Bertsekas has focussed on two areas: computational methods for optimization problems, and parallel and distributed algorithms.

In the area of computational methods for optimization problems, Professor Bertsekas and his co-workers have investigated projection methods for constrained optimization, coordinate ascent and decomposition algorithms for large-scale linear and nonlinear programming, interior point methods for linear programming, and linear and convex network optimization methods. This work has aimed primarily at the development of methodology for solving large-scale problems. Many of these problems have structures that are amenable to decomposition and parallelization, and they often involve a graph structure and/or a dynamic system structure. In the former case, the number of nodes and arcs is often very large, while in the latter case, problems of large dimension often arise because of the underlying time and/or space discretization of a differential equation. Both graph structures and dynamic system structures have been extensively considered in this work.

In the area of parallel and distributed algorithms, Professor Bertsekas and his co-workers have investigated communication issues in interconnection networks of parallel processors. In particular, they have investigated some basic communication problems that arise in many algorithmic contexts, auch as multinode broadcast and total exchange. The effect of randomness of packet length and arrival time of messages was quantified in the context of some common architectures such as hypercube and mesh. They have also established general frameworks for convergence analysis of distributed asynchronous iterative processes, and they analyzed several specific algorithms relating to shortest paths, dynamic programming, gradient methods, and network optimization.

Roger Brockett

During this period, Professor Brockett and his students performed experimental and theoretical work in the areas of robotics, computer vision and analog computation. Highlights of the work on robotics include the use of new geometrical methods (harmonic mappings) for the design of kinematics (Frank Park), and Bayesian inversion algorithms for the interpretation of tactile sensing data (William Nowlin). In the area of computer vision the work included the development of real-time algorithms for the motion from moments problem (Morris Lee), and the development of robust matching algorithms based on minimal stress interpolation (Ed Rak). Developments in analog computing include the proof that a variety of combinatorial problems can be solved by a relatively simple class of ordinary differential equations, and that it is possible to use differential equations to simulate finite automata in a reasonably straight forward way. The work of Faybusovich clarified the role of interior trajectory methods for linear programming and provided new algorithms. New work on the design of neural networks based on the propagation of the conditional density shows that the double bracket equation can be thought of as providing the optimal data for solving certain types of sorting problems involving noisy data. Finally, the properties of a new class of filters that discriminate on the basis of the way the energy in a signal is distributed among various subspaces were defined and studied. It was shown that these adaptive subspace filters can be used to solve problems in system identification and signal detection.

Munther Dahleh

During this period, Professor Dahleh was involved in two major problems. The first was the development of a robust control methodology in which realistic time-domain specifications can be incorporated systematically in the presence of plant and input uncertainty. Algorithms based on linear programming computations were developed. This methodology was extended to incorporate *Hybrid* systems, i.e. continuous-time systems with digital controllers, otherwise known as sampled-data systems. The second problem was the study of system identification in the presence of bounded but unknown noise. In particular, the objective was to study the problem of worst-case identification. The motivation behind this problem is the desire to use a given model in robust control applications. In this case, the model should approximate the actual process in a strong sense, which is not generally possible with the traditional identification schemes. Results in this direction showed that one can devise fairly simple algorithms that guarantee a small error between the estimate and the process for a fairly general class of model sets, provided that the inputs are chosen appropriately. A study of the complexity of such algorithms was conducted.

Professor Dahleh had extensive interactions with Dr. Normal Coleman and his group at ARDEC, through various tutorials and workshops. This interaction between LIDS and ARDEC took a big step ahead when the center hired Dr. Dragan Obradovich as a postdoctoral associate, supervised by Prof. Dahleh. Since then, both have been heavily involved in a controller design for a gun that will be mounted on top of an aircraft. This control problem highlighted new and interesting directions for research, particularly in the problem of identification within uncertainty.

Wendell H. Fleming

During this period, Professor Fleming and his students and postdoctoral fellows conducted analytical and numerical studies of topics in applied probability, stochastic control and nonlinear estimation. In applied probability, sharper versions of Freidlin-Wentzell large deviations formulas in the form of WKB-type asymptotic series were obtained. A combination of probabilistic and partial differential equations (PDE) methods were used. In stochastic control, finite difference approximations to dynamic programming PDEs were studied, for models with a special structure which facilitates proofs of convergence of optimal feedback control policies. Risk-sensitive stochastic control problems and their connection with robust nonlinear control were studied, using viscosity solution methods for nonlinear PDEs. In addition, stochastic control problems were considered in a convex duality framework.

Nonlinear filtering problems were studied in cases where a piecewise one-to-one function of a system state plus low intensity white noise is observed. Sequential hypothesis tests to discriminate among regions in which the observation function is one-to one were developed. The small observation noise analyses provide justification for ad hoc approximate filtering techniques such as extended Kalman Filters and their extensions.

Robert Gallager

Professor Robert Gallager worked on an information theoretic investigation of broad band communication channels (both point-to-point and multiaccess). Given an energy constraint, the reliability function of such point-to-point channels has been found exactly in the limit of an unbounded number of degrees of freedom.

These results have been extended to multiaccess channels, where results shed light both on the issue of multiaccess decoding and on the relationship between spread spectrum and random access communication. Professor Gallager also worked on performance guarantees and congestion control in high speed networks, and (with John Spinelli) on failure recovery protocols in networks, investigating methods for a computer network to provide reliable communication when some of its components may fail.

Stuart Geman, Basilis Gidas, Ulf Grenander, and Donald McClure

The Brown University Pattern Theory Group's work has concentrated on the development of rigorous mathematical foundations for problems in computer vision and image analysis. Principals of the group include S. Geman, B. Gidas, U. Grenander and D. McClure. A general theme of the research is to guide the development of algorithms and the solution of computational problems by carefully articulated mathematical models.

Probabilistic models and principles of Bayesian inference are cornerstones of the group's approach to problems in image analysis. Predominant among the probabilistic models used are Markov Random Fields (MRFs). There are several important instances of the use of Markov processes in computer vision and image processing by others in the early 1980s and earlier. This group played an important role in fashioning the rigorous mathematical framework on which the MRF/Bayesian approach rests, starting around 1983. Early contributions included:

(i) the crystalization of the Markovian framework,
(ii) the recognition of the Markov-Gibbs correspondence and its importance for modeling and for designing and understanding computational approaches,
(iii) the definition of Monte-Carlo methods for sampling from Gibbs distributions, and
(iv) the first proofs of convergence and divergence of simulated annealing as a method of global optimization.

These advances encouraged the use of well-founded probabilistic and statistical methods in image analysis.

The focus of the group's research has evolved from the early phase that emphasized low-level image processing and simple lattice-based MRFs to a current focus on the development of richer mathematical models and high-level computer vision problems. The completed research has included basic foundational issues for Markov processes, important for understanding how broadly the use of Markov models can be justified, as well as preliminary work on probabilistic models for shapes which exhibit global structure/regularity and, at the same time, high degrees of variability from instance to instance -- e.g. a human hand and other biological forms.

The groups research has emphasized the development of mathematical tools, some motivated by intrinsic mathematical interest and some by applications. The modeling approaches have been strongly influenced by applications. In completed research, the utility of MRFs for modeling low-level regularities in images was driven by applications to automated industrial inspection and emission computed tomography. The applications stimulate the mathematical research and, in turn, the algorithms derived from the mathematical analysis provide new methodological approaches for the applications.

In the area of foundations, a comprehensive presentation of general pattern theory (by Grenander and Miller) has recently been completed and is in the process of final editing for publication. The volume describes the unified theory for regular structures developed by the author over the past twenty-five years. In very recent work (Gidas and Hudson; Raphael), the issue of how generic so-called hidden Markov models (HMMs) are has been addressed. This work has made extensive use of Markov processes as models for grey-level distributions, boundaries, textures, isotope concentration maps, and, more recently, for shapes in reconstruction and recognition experiments. In these settings, as well as in Markov-based speech recognition, the actual observations are functions of a Markov process, thereby "hidden Markov," with a rich and complex dependency structure. At the same time, the basic building blocks for the process exhibit simple, local Markovian dependence. Therein lies the utility of HMMs. Key results cover

(i) the approximation of an arbitrary stationary process with finite state space and indexed on a d-dimensional lattice by a nearest-neighbor HMM, in the topology of weak convergence, and

(ii) consistency results for nonparametric estimation algorithms to fit HMMs to observations of an arbitrary stationary process.

In the area of learning and parameter estimation, an important step in applications of the group's framework is the estimation or "learning" of Markov random fields from (possibly degraded) data. The estimation problem for Markov random fields generalizes in a fundamental way that of time series and has motivated the design of computationally efficient algorithms (by Almeida and Gidas). It has also led to interesting mathematical problems for consistency and asymptotic normality, whose partial resolution (by Geman; Geman and Gidas; and Grenander) has involved large deviation techniques, a new variational principle, and tools from statistical mechanics. The nonparametric learning problem for large, complex systems (e.g. neural nets) was also considered (by Comets and Gidas); attempts to estimate large numbers of parameters in neural networks are seen in the context of standard nonparametric estimation and regression, thereby drawing on a substantial and well-established theoretical base and exposing some fundamental limitations implied by the "bias-variance" dilemma and other tradeoffs.

In the area of algorithm design, analysis and optimization, the basic stochastic relaxation algorithms developed in the group's earlier work proved to be broadly applicable, even if not highly efficient, and stimulated extensive mathematical research on convergence and computational complexity. In recent research, motivated by the need for algorithms well-suited to more highly structured models, group members have developed:

(i) a multistage/mutiresolution algorithm based on the Langevin equation (by Amit, Grenander, and Piccioni; Amit and Piccioni); and

(ii) a jump-diffusion algorithm for recognizing an a priori unknown number of deformable objects (e.g. mitochondria) in a scene (e.g. an electron micrograph) (by Manbeck).

The latter algorithm has been implemented on a NEWS architecture SIMD parallel system, enabling real-time video monitoring of its behavior. A fundamental theoretical issue addressed by Manbeck, and a recurring analytical question, is to prove the ergodicity of the associated Markov process. Virtually all of the computational work by our group has dealt with questions of convergence and efficiency of simulation and optimization algorithms. In addition, regular interactions with visiting scientists have stimulated important contributions by groups in Rome, Paris and Taipei on convergence properties of Monte-Carlo procedures for sampling from Gibbs distributions.

In the area of deformable templates and object recognition, the group has explored a model-based approach to nonrigid object recognition. The required models must address both the global structural characterization of an object and the class of transformations that define the possible presentations of the object. It has proposed a class of such models (Comets and Gidas; Amit, Grenander, and Piccioni), which it calls deformable templates, and has performed preliminary experiments to test their utility in a variety of applications (Comets and Gidas; Amit, Grenander, and Piccioni; Manbeck). The study of deformable templates, and associated algorithms for template matching in object recognition tasks, has stimulated a number of theoretical investigations (Amit; Gidas and Hudson; Amit and Piccioni), which have yielded results on diverse topics. These include some new coarse-to-fine type methods for Monte Carlo simulations, and the aforementioned result establishing the density, among all stationary processes in arbitrary dimensions, of hidden Markov models.

In the area of ill-posed inverse problems, the group continued to study ill-posed inverse problems using stochastic regularization and Bayesian inference, focusing on applications to medicine and astronomy. The work by Chow, Gidas, Grenander, Hudson, Keenan, Raphael, and Torreao involves single photon emission computed tomography. A comprehensive physical model was developed, which includes corrections for attenuation and scattering; all experiments involve either real or physical phantom data. In addition, scaling properties of the regularization term are derived by computing the continuum limit of the associated prior distribution. In contrast, other work addressed a "dual" of the tomographic reconstruction problem: determining the radiation dosage and treatment design necessary to achieve or approximate as closely as possible a specified uptake distribution.

In the area of image processing and recovery of low-level structure, the group's previous work in machine vision has emphasized mathematical methods for "low" and "medium" level image processing tasks, such as those involving the ill-posed inverse problems discussed above. Models and associated computational algorithms have been developed for a number of potential applications, including boundary detection and artifact removal for film restoration (Geman, Manbeck, and McClure), shape from shading (Grenander and Miller), and image representations with bivariate splines (Torreao). Group members explored the use of spatial-temporal MRFs for the problem of restoring and enhancing video sequences degraded by intra-frame artifacts (e.g. dirt on the original film) and by frame-to-frame artifacts (e.g. scratches). The inclusion of motion-compensated inter-frame bonds in the underlying MRF graph structure enables the expected temporal continuity to detect and remove noise and artifacts.

Several recent books and review articles describe the spatial statitics/Bayesian framework for image analysis. The two volumes by Grenander and Miller, and Hwang, Hwang-Ma, and Sheu, contain a systematic treatment of general pattern theory, mathematical studies of simulation and optimization algorithms, and a host of applications, while the paper by Geman, Geman, and McClure contains a detailed exposition of various inverse problems in image analysis, approaches to these problems within the groups framework and by alternative methods, and basic properties of stochastic relaxation and simulated annealing. Finally, the book by Grenander is a comprehensive exposition of mathematical tools and properties concerning Metropolis-type Monte-Carlo simulation algorithms and simulated annealing in the context of the general theory of stochastic processes and Markov chains.

Y.C. Ho

During this period, the support of the center for intelligent control helped to establish the subject of Discrete Event Dynamic Systems (DEDS) as a full-fledged intellectual discipline. Professor Y. C. Ho's group at Harvard, chiefly responsible for creating the subject, accomplished nine Ph.D. theses, three published books, three awards for best paper or book, one videotape tutorial, one new international journal on DEDS, two conferences on DEDS sponsored by NSF, 63 invited talks, three plenary addresses at world congresses, one IEEE Control Engineering and Science Field Award, and one membership in the National Academy of Engineering. There were three references to DEDS as a discipline for the 90s in white papers by SIAM, ORSA and IEEE.

During the period covered by this report, the following theses were written: Equivalence methods in the perturbation analysis of queueing networks (Paul Glasserman); Three topics on perturbation analysis (Pirooz Vakili); Optimization of queueing systems using perturbation analysis (Michael C. Fu); Strong consistency of perturbation analysis estimates (Jian-Qiang Hu); Comparison methods for scheduling control of multiclass queues (Gerald E. Feigin); Extended perturbation analysis of discrete event dynamic systems (Shu Li); Performance gradient estimation for very large Markov Chains (Bin Zhang).

Discrete Event Dynamic Systems (DEDS) constitute an important topic of control system study. Examples of DEDS range from large international airports, to computer communication networks, to manufacturing plants, logistics and service systems, and C^3I systems. The design, performance evaluation, and operations management of such man-made systems are a fertile field of research. The Harvard group, under the direction of Professor Ho, initiated a systematic study of such problems, resulting in the creation of the areas of perturbation analysis, parallel simulation, and ordinal optimization. These techniques promise to usher in a new paradigm for the optimization, design, and on-line control of DEDS.

The intellectual foundation and visionary aspect of the subject of DEDS have been previously described and can be most easily accessed via the videotape tutorial (#HV0238-6 by Y.C. Ho) published by the IEEE Educational Services.

Harold Kushner

Professor Harold Kushner and his students worked on a rigorous and systematic approach to the problem of optimal tracking via "minimizing escape probabilities" over a given time interval, for small noise systems, using the theory of large deviations; diffusion approximation for queues, production and repair systems working in a heavy traffic environment; and approximations to optimal repair and maintenance policies for the above based on noisy samples and small information per sample.

Professor Kushner and his co-workers sought numerical methods for a great variety of stochastic control problems. Their method involves the systematic approximation of the optimal control process by a simpler one which is manageable from a computational point of view. In particular, the use of some Markov chain models enables the utilization of a wide literature on the solution of Markov problems. The approximation must be consistent with the underlying diffusion or jump-diffusion in the sense that the local properties must match for the controls of interest. Both the drift and the variance terms can be controlled; this is, in fact, the first appearance of methods which can be used when the variance is controllable. Models that require such control occur all through "financial economics," waveform design, the control of observer location in filtering problems, etc. A great deal of attention was given to numerical methods for use in production and queueing systems under heavy traffic. The proofs are very natural from the point of view of the probabilistic problems that are considered, and give considerable insight into the nature of the approximation procedure and the sorts of results which can be obtained.

Petros Maragos

During this period Professor Maragos and his collaborators performed research in the areas of signal processing, computer vision, computer speech, and pattern recognition. In the area of signal processing, the new developments include a unifying representation theory for large classes of nonlinear filters using morphological systems; a theory and an efficient algorithm for computing the fractal dimension of arbitrary signals using multiscale morphological filters (with F.-K. Sun); and nonlinear partial differential equations of the evolutionary type that model the dynamics of multiscale morphological filtering in scale space (with

R. Brockett). The work in the area of computer vision includes the application of morphological size distributions to multiscale nonlinear image smoothing, shape representation and description; an efficient system for region feature extraction and segmentation in moving imagery with related correspondence algorithms (with C.-S. Fuh and L. Vincent); a robust image matching algorithm based on an affine model (with C.-S. Fuh); and methods for analysis and modeling of fractal images using morphological systems. In the area of pattern recognition several interesting relationships have been found between machine learning theory and mathematical morphology. The min-max pattern classifiers were developed as extensions of Boolean classifiers for real-valued features, and applied to the recognition of hand-written character images; their learnability properties were studied (with P.-F. Yang).

The work in computer speech processing and recognition includes the use of fractals for feature extraction and modeling -- e.g. the use of the short-time fractal dimensions of speech signals for segmentation, interpolation, and recognition (with M. Lu), and the use of fractal signals as excitation of stochastic speech coders (with K. Young). In addition, a new algorithm has been found for tracking amplitude/frequency modulations in speech resonances based on energy operators (with J. Kaiser and T. Quatieri). The low computational complexity and efficiency of this algorithm for amplitude and frequency demodulation, as well as its instantaneously-adapting nature, make it very useful for tracking modulation patterns in time-varying signals.

Sanjoy Mitter

Professor Sanjoy Mitter's main research has been on the study of perceptual systems (image analysis and vision, speaker independent speech recognition, off-line handwritten character recognition) and on cognition (learning). In image analysis and vision he has worked on boundary detection using variational and probabilistic methods, texture segmentation using multi-scale probabilistic ideas and most recently on developing a language for low and mid-level vision. In speech recognition he is cooperating with Ken Stevens of M.I.T. in developing a speech recognition methodology which uses a priori knowledge in the form of linguistic features and incorporates it in an appropriate probabilistic framework. His work on handwritten character recognition uses an information-theoretic framework for the recognition of handwritten character recognition.

In the area of learning his main work has been in the extension of the PAC learning framework of Vapnik and Valiant to solve problems in stochastic geometry using learning ideas.

In a series of papers written jointly with Saul Gelfand (Purdue University, formerly at CICS) he has studied stochastic recursive algorithms (stochastic gradient-like, Metropolis) for the minimization of a function in $\mathbf{R}^d$.

A number of research assistants, center fellows and post-doctoral associates have contributed to this research. These include Sanjeev Kulkarni, Pietro Perona, Thomas Richardson, Mohamed Akra, Stefano Casadei and Ellen Eide.

David Mumford

Professor Mumford and his students (Yang Wang, Gaile Gordon, Mark Nitzberg, Peter Hallinan, Peter Belhumeur, Tai-sing Lee, and David Fry) have been working the area of computer vision and animal/human vision.

A substantial part of this work has concerned development of a Bayesian approach to figure/ground separation, due to S. and D. Geman, A. Blake, A. Zisserman, and D. Mumford. This approach uses ideas from statistical physics and works by constructing a Gibbs probability distribution on the space of all images and their natural segmentations. Prof. Mumford and Jayant Shah investigated a continuous analog of the lattice based random fields of statistical physics. Yang Wang's work investigated limits of this algorithm which are close to the classical "split and merge" segmentation algorithms and also found key estimates for the problem of proving regularity of the maximum liklihood segmwentations. Mark Nitzberg's work extended the above model to analyze occlusions in segmented images, using "T-junctions" (points where one object edge disappears behind a nearer object) as the major clue. Peter Belhumeur's work extends these ideas to stereo data, using a Bayesian prior and "unmatched pixels" (points visible to one eye only) as the major clue. Tai-sing Lee's work extends these ideas to texture segmentation, using Gabor filters, with special emphasis on FM signal modulation: the presence of slowly varying spatial frequencies resulting from textures present on sloping surfaces.

A second line of research has pursued the problem of recognition of shape. There are many questions here: What is the meaning of the phrase "two shapes are similar"? What "features" of a shape are most useful for recognition? How does one match one's models of shapes with the data? We have used especially location and recognition of faces as a good instance of these problems. Gaile Gordon worked on recognition of individuals from laser range data of their faces. She analyzed the use of the principal curvatures and other differential-geometric invariants for recognition. Peter Hallinan, on the other hand, has been working on the problems of finding the optimal match between an intensity template for a face, in which various degrees of freedom are allowed, with an unknown image. Finally David Fry has taken leaves rather than faces as a test bed, and has developed an algorithm of species recognition based on matching which allows reshuffling of parts, but penalizes the amount of translation and rotation of each part before reassembling.

A final line of research concerns analogies between the problems and algorithms of computer vision and the data from animal and human vision: psychophysical, neurophysiological and neuroanatomical. Prof. Mumford has developed a theory of what algorithms are embodied in what parts of the brain which is based on many known experimental results and which predicts others.

Ronald L. Rivest

Professor Ronald L. Rivest worked on the theoretical foundations of machine learning. He studied a number of different models, ranging from neural nets to distribution-free learning paradigms to the inference of finite-state systems.

With Javed Aslam, he worked on the algorithmic inference of Markov chains. With Sally Goldman and Robert Schapire, he studied the problem of learning a binary relation, i.e. a predicate relating the elements of two sets. With Robert Ramstad, he worked on an efficient reimplementation of Drescher's learning method, which provides a computational interpretation of Piaget's theory of early human learning. With Yigun Yin, Professor Rivest developed and experimentally tested a new heuristic for the "two-armed bandit problem." With Tonu Kuh and Thomas Petsche, he studied the problem of learning concepts that "drift" or "vary" slowly over time. With Bonnie Eisenberg, he worked on learning from both random examples and membership queries, and proved that membership queries are not generally useful, unless there is prior knowledge about the probability distribution according to which the random examples are drawn. With Robert Schapire and Michael Kearns, he studied some problems related to Valiant's distribution-free learning model, and discovered some new approaches to learning.

Charles Rockland

Charles Rockland and his collaborators continued work on the partial models and constraints framework for representing complex system organization. A basic emphasis of this research was to clarify the differences in the formalisms required for natural vs. artificial systems. This work took two forms:

(i) They continued their exploration of analogies with the so-called principles and parameters approach to natural language.

(ii) In collaboration with Bernard Gaveau (University of Paris, VI), they began investigation of the issues underlying the behavioral specification of complex interactive systems. Part of this work centered on identifying the circumventing deficiences of existing formalisms, such as Milner's CCS, developed for artificial systems.

John Tsitsiklis

Professor John Tsitsiklis and his co-workers have carried out research in a number of areas discussed below, as well as certain operation research applications and distributed detection and estimation.

In the area of parallel and distributed computation, they have carried out a comprehensive study of asynchronous distributed algorithms for optimization and other numerical problems. They have developed a comprehensive convergence theory, and have also studied issues related to speed of convergence. A main conclusion of this study is that a plethora of useful algorithms retain their desirable convergence properties in the presence of asynchronism and fairly chaotic interprocessor communication.

On another topic, they have formulated and solved a number of generic routing and scheduling problems that arise when we try to optimize interprocessor communication in parallel architectures, especially hypercubes.

A great part of the work in these areas has been incorporated in a major textbook on parallel and distributed computation co-authored by Professors Bertsekas and Tsitsiklis.

In the area of simulated annealing, Professor Tsitsiklis and his collaborators have provided an alternative convergence proof of convergence. By establishing a link with the theory of Markov chains with rare transitions, this proof has provided a new way of understanding the function of this algorithm.

In the area of control theory and computational complexity, a number of problems in control theory, such as supervisory control of discrete-event dynamical systems and discrete--time stochastic control, have been studied from the viewpoint of computational complexity theory. For a concrete example, they have shown that a one-way multigrid algorithm is optimal, in a precise sense, for solving discrete-time stochastic control problems for the case of continuous state spaces.

Leslie Valiant

Professor Leslie Valiant investigated the question as to which classes of concept representation it is computationally feasible to learn from examples. Learnability is not monotonic in the class of representations; if the latter is enlarged, there is more to be learned, but the task may become easier because there is now a richer representation for expressing it. In collaboration with co-workers, Professor Valiant obtained some general properties of learnable classes. In particular, they obey certain closer properties and are preserved under certain substitutions. Also, strong statements can be made about the effect of having both positive and negative examples available, as opposed to examples of just one kind. The effect in some instances is to render learnable what otherwise is not. In other cases, it reduces the number of examples required, or it increases the error rate that can be tolerated in the data.

Alan Willsky

During the period covered by this grant, Professor Willsky, Dr. Karl, and their students engaged in research in discrete-event systems and in a number of problem areas in multidimensional statistical signal processing and estimation. In the area of discrete-event systems, the major accomplishments are summarized in the Ph.D. thesis of Dr. Cuneyt Ozveren and in a series of papers published by Prof. Willsky and Dr. Ozveren. This research developed a notion of stability for discrete-event systems and explored its consequences in feedback system design, system monitoring, compensator design for command following, and hierarchical modeling based on the concept of macro-events or "tasks". Both Dr. Ozveren and Prof. Willsky have given several invited talks on this work including Dr. Willsky's presentation at the 1991 ARO-Concepts Analysis Agency Workshop on Combat Modeling. Dr. Ozveren also received honorable mention in the IEEE Control Systems Society Student Paper Contest for a conference paper based on the initial results in his thesis.

The research of Prof. Willsky and Dr. Karl in multidimensional statistical signal processing and estimation has several components. The first of these is in the development of efficient and highly parallelizable algorithms for multidimensional estimation. In particular, essentially all multidimensional estimation problems involve potentially explosive computational demands, caused both by working in multiple spatial dimensiona and by the compounding lack of an obvious notion of recursion. The work in this area, as summarized in the Ph.D. theses of Dr. Darrin Taylor and Dr. T. Michael Chin, and the S.M. thesis of Mr. Michael Daniel (in progress) as well as in several papers written by Prof. Willsky together with Prof. B.C. Levy (University of California at Davis) and Dr. R. Nikoukhah (INRIA, France), deals both with new notions of recursive computation in multiple dimensions, with parallelization achieved by data partitioning and a generalization of the technique of nested dissection for solving partial differential equations, and with effective methods for dealing with processes that evolve in time as well as in space. In particular a new approach using radial recursions has been developed and demonstrated to yield efficient and accurate solutions which could then be coupled with spatial data partitioning to produce a new class of multidimensional parallel processing algorithms. In the area of space-time processes, a key contribution was the recognition that the major computational problem, namely that of calculating error covariance functions for predicted spatial fields and using this to specify the procedure for incorporating new measurements, could be viewed as one of statistical modeling of random fields. This led to very effective methods for reduced-order modeling allowing the solution of space-time estimation problems of very high dimension -- e.g. 500,000. Professor Willsky's experimental research in this area has demonstrated not only the efficiency but also the accuracy of the solutions produced by this method for the problem of motion estimation in image sequences. In addition, his work on multiresolution methods described subsequently offers even greater computational efficiencies, which, when coupled with the research just described now makes possible the consideration of problems of sizes far larger than any considered previously.

A second component of his research in multidimensional processing and estimation is in the foundations, theory, and application of a methodology for multiresolution statistical modeling and estimation motivated by and closely related to wavelet transforms. This work is documented in the Ph.D. theses of Dr. Kenneth Chou, Eric Miller, Mickey Bhatia, and Mark Luettgen (in progress) and the M. Eng. theses of Stuart Golden and Ilya Polyak (in progress) as well as in numerous papers by these individuals, Prof. Willsky, and Dr. Karl. The basis of this work is the introduction of a class of scale-recursive models for stochastic processes and random fields. These models lead to extremely efficient algorithms both in one and several dimensions. Indeed this work on multiresolution motion estimation has resulted in algorithms that have constant complexity per pixel, providing between one and two orders of magnitude of computational speed-up over previously developed methods. In addition, this multiresolution modeling framework is rich enough to capture an extremely broad class of processes and random fields. In particular, it is possible to model fractal-like or so-called *"1/f"* processes in this framework, leading to a new class of "fractal regularization" algorithms. In addition, Professor Willsky and his collaborators have shown that a generalization of Levy's so-called midpoint deflection construction of Brownian motion provides the basis for the exact multiresolution modeling of arbitrary Markov random fields and for extremely compact and computationally attractive approximate modeling, opening up the possibility of extremely efficient algorithms for task such as image segmentation and texture identification. In addition, their multiresolution methods also offer considerable promise in the area of inverse problems, described below.

The third component of Professor Willsky's research is in the estimation and reconstruction of geometric features in multidimensional data. This work is documented in the S.M. theses of Seema Jaggi and Lori Belcastro (in progress) and the Ph.D. theses of Dr. Karl and Peyman Milanfar (in progress) Major contribution in this work include the development of a methodology for the reconstruction of 3-D objects from their 2-D silhouettes, and the tracking of objects with time-varying shape. This methodology has been proven to work in practice resulting in a new approach to temporal imaging of the heart give very low-dose (and thus low SNR) imagery. They have also developed new approaches to the direct extraction of geometric information from tomographic data, which also provide new algorithms in computational geometry that directly accommodate, and hence are robust to, uncertainties and errors in the observed data.

The final part of this research is in the development of statistical methods for inverse problems in one and several dimensions. In particular, multiresolution methods have been applied to problems of one-dimensional multisensor deconvolution and fusion (Eric Miller) and tomography (Mickey Bhatia), while our work on geometric reconstruction from tomographic data (Peyman Milanfar and Lori Belcastro) provides new algorithms for inverse Radon transforms based on nonlinear (i.e. geometric) parametrizations of the field to be estimated.

This group's work in multidimensional statistical signal processing and estimation has received considerable national and international attention as evidenced by numerous invited lectures and keynote addresses that Prof. Willsky has given in this area as well as by his guest editorship of the recent special issue of the *IEEE Transactions on Information Theory* on wavelet transforms and multiresolution signal analysis. Among Prof. Willsky's invited lectures are plenary and keynote lectures at the Seventh Army Conference on Applied Mathematics and Computing in 1989, the 1991 IEEE International Conference on Systems Engineering, the 1991 SIAM Conference on Linear Algebra and Its Applications and the Opening Ceremonies and Workshop for the National Cooperative Research Centre on Robust and Adaptive Systems in Canberra, Australia in February 1992.

Alan Yuille

During this period Professor Yuille and his collaborators and students performed theoretical and experimental work in the areas of computer vision and neural networks. Highlights of this work include:

(i) the development and the application of deformable template models to the detection of facial features, automatic diagnosis from medical images, and the detection of particles in high energy physics experiments;

(ii) the application of Bayesian ideas to computer vision including image segementmentation and binocular stereo vision;

(iii) demonstrating a relation between Bayesian theories of stereo vision and psychophysical experiments;

(iv) the development of a Bayesian framework for sensor fusion (with Prof. J.J. Clark);

(v) self-organizing neural network models for development of structures in the early visual cortex; and

(vi) showing that by putting neural network model within a statistical physics framework one could obtain more effective algorithms and demonstrate hitherto unexpected relationships between existing models.

10.0 INTERACTIONS WITH ARMY RESEARCH OFFICE AND ARMY LABORATORIES

Numerous individual interactions between Army Laboratory personnel and Center faculty take place each year. These interactions can be categorized as:

(i) Substantive interactions extending over long periods of time

(ii) Short courses presented at the request of Army Laboratories

(iii) Participation in Army-organized conferences and workshops

The following sections describe these interactions in greater detail.

10.1 Substantive joint work extending over long periods of time

Representative programs here are:

CICS/Martin Marietta/Human Engineering Laboratory Joint Work on the Field Material Handling Robot (October 1988 to date)

Dr. Pierre Dupont's experience as a Postdoctoral Associate with the Center is an example of how interaction between academia, industry and government can prove beneficial to all. In response to a request for Center assistance by Martin Marietta Aero & Naval Systems, Dr. Dupont aided Martin Marietta's engineers in the dynamic modeling and controller design of the Field Materiel Handling Robot (FMR), being built under contract for the US Army Human Engineering Laboratory.

In particular, Dr. Dupont developed friction models for the transmission elements of the FMR. These models were verified experimentally by Martin Marietta and included in both their simulation software and in the FMR's feedforward control law. In addition, general procedures for simulating friction, especially load-dependent friction, were developed.

The FMR project has led Dr. Dupont to begin work on several other friction-related topics. One of these involves the control of steady, low-velocity motion. While the FMR is primarily a gross-motion machine, there are many situations, such as those involving dextrous manipulation, when fine-motion control is paramount. In these cases, the transient effects of friction, typically ignored by control theorists, play an important role in determining controller requirements for avoiding stick-slip.

A second topic concerns the existence and uniqueness properties of the forward dynamic solution with friction -- the problem which must be solved to simulate the motion of a system. Friction can cause the Newtonian formulation of certain rigid-body dynamics problems to break down. In these situations, a problem can appear to have no solution or, through the use of solid mechanics, to have multiple solutions. Dr. Dupont is investigating a new class of problems which possess multiple valid solutions due to friction.

CICS/ARDEC Joint Work on Systems Dynamics and Control (June 1990 to date)

Dragan Obradovic, a postdoctoral fellow with the Center, worked with Dr. Norman Coleman's Laboratory at ARDEC on a project whose goal is to improve the accuracy of the heliborne gun/turret system by using state of the art control technology. This is to be achieved by deriving a sufficiently accurate system dynamics model that captures all the important phenomena occurring during the firing instances.

In particular, Dr. Obradovic has worked on improving the existing models of the gun/turret dynamics and adjusting them to a form suitable for the robust control design. These models, derived by Integrated Systems Incorporated and Lear Astronics Corporation, subcontractors on the same project, are proven to be accurate only at a very limited range of frequencies. Consequently, they do not capture the flexible modes excited during the firing that are considered to be the main source of disturbance in the system. Therefore, the work of Dr. Obradovic focuses on obtaining a better description of the gun/turret dynamics during the firing by both analytical and experimental approaches and on characterizing the uncertainty associated with the model.

This project has led Dr. Obradovic to begin working on other topics concerning system identification and model validation for robust control design. In the case of deterministic, unknown but norm bounded disturbances, system identification in general does not lead to a single model but to a set of possible models. Dr. Obradovic is investigating how the a priori knowledge about the actual system and choice of the input signal used in an experiment influence the result of the identification.

10.2 Short courses presented at the request of Army Laboratories

In addition to regularly scheduled Center-organized workshops, Center faculty have presented a number of short courses at the request of various Army Laboratories. Among them are:

(i) Two-day short course on Nonparametric Statistics presented by Professor Stuart Geman at the Army Engineering Waterways Experiment Station.

(ii) Two-day short course on Theory of Large Deviations presented by Professor Daniel Stroock at the University of Maryland.

(iii) Two-day short course on Nonparametric Statistics and Applications to Image Analysis presented by Professor Donald McClure at the U.S. Army Engineers Waterways Experiment Station, Vicksburg, Mississippi.

(iv) Tutorial on Modern Control Systems Design using the Q-parametrization presented by Professor Munther Dahleh at ARDEC.

10.3 Participation in Army-organized conferences and workshops

Center faculty are regularly asked to speak in the Annual Army Conference on Applied Mathematics and Computing. For example:

At the Fifth Army Conference at West Point, 1987, Professor Sanjoy Mitter spoke on "Stochastic Quantization," Professor Gilbert Strang on "Structural Optimization and Composite Material in Optimal Designs," and Professor David Mumford on "Some Mathematical Problems Arising from Computer Vision."

Professor Alan Willsky spoke on "Estimation for Multidimensional Random Fields" at the seventh Army Conference in 1989.

Professor Mitter was again invited to speak at the eighth Army Conference in 1990 on "Variational Problems with Free Discontinuities and Nonlinear Diffusions."

In addition, Center faculty are regularly invited to participate in other Army-organized workshops and conferences, for example:

Professor Stuart Geman spoke on "Hidden Markov Models for Image Analysis" at the ARO-sponsored Encounter of Computer Vision and Mathematics Workshop, May 21-23, 1990, at the University of Pennsylvania.

Professor Roger Brockett presented an invited talk at the Ninth Army Mathematics Conference in June 1991.

10.4 Individual Interactions

Numerous individual interactions between Army Laboratory personnel and Center faculty take place each year. For example, over the past year, the following interactions were reported:

Professors Alan Willsky and Y.C. Ho participated in a meeting in May 1990 at the U.S. Army Materiel Command in Alexandria on the use of recent results on discrete event dynamic systems.

Professor Y.C. Ho also had discussions with Richard Chait, Chief Scientist, Army Material Command, on May 22, 1990. He met with scientists from the Army Material Systems Analysis Activity at the Aberdeen Proving Ground in June 1990. He also visited the AMC Headquarters in Washington, D.C., and the Aberdeen Proving Ground. He interacted with Aberdeen personnel on various logistics and tank ground war problems involving simulation, and was invited to speak on June 5, 1990.

Dr. Paul Tseng had discussions with Joel Levy, Operations Research Analyst at the US Army Concepts Analysis Agency, on the potential of using network flow methods to solve a warehouse allocation problem.

Professor Munther Dahleh has had extensive interaction with Norman Coleman, ARDEC, and CICS postdoctoral fellow Dragan Obradovic, regarding a controller design for a gun that will be mounted on top of an aircraft. This control problems highlighted new and interesting directions for research, particularly in the problem of identification within uncertainty. Dr. Obradovic presented some of these ideas at the meeting in November organized by Dr. Jagdish Chandra, ARO.

Professor Donald McClure has continued to consult with scientific staff at the Center for Night Vision and Electro-Optics on image processing problems.

Professor Basilis Gidas met with a number of the Army personnel (including Dr. Chandra) at W.J. Schaeffer Associates Inc., Rosslyn, Virginia, and discussed possible applications of CICS work to the Army, and in particular, to SDI problems. Prof. Gidas also discussed his views on new directions in multiresolution-multiscale phenomena in computer vision and dynamical systems in August 1990. During the fall of 1990, Prof. Gidas had contacts with Dr. Jerry Andersen of ARO to establish connections with members of the laboratory and industry in relation to his work on the analysis of Synthetic Aperture Radar data.

11.0 MECHANISMS FOR EXCHANGING TECHNICAL INFORMATION

It is our goal that the Center for Intelligent Control Systems (CICS) should serve as an educational and research resource for the Army as well as function as a national center for fundamental research in Intelligent Control Systems.

An important aspect of the Center is its role as a meeting ground for researchers from the Army Laboratories, the Center and from outside. Interactions involving Army Laboratory personnel take place in scholarly meetings such as research reviews, workshops and colloquia, and, individually, in interactions between Center faculty and army researchers working on particular problems or issues. Information about research activities in the Center is also disseminated in print, in the form of CICS Technical Reports, the newsletter *The Intelligent Control Letter*, and other mailings.

The listing below summarizes the various mechanisms for the exchange of technical information with the Army's researchers.

(i) Research Reviews

(ii) CICS Workshops

(iii) Colloquium Series

(iv) Publications Program

(v) Interactions with Army Researchers (long-term, short-term)

In the following sections, we document these mechanisms in greater detail.

11.1 Research Reviews

The yearly or biannual Research Reviews provide an overview of current CICS research and include technical presentations by both Army scientists and engineers and CICS faculty. Because Research Reviews are scheduled for an entire day, with time held for informal contact, they are an excellent opportunity for lengthier interactions between Center faculty and Army researchers. Listed below are the 8 research review meetings that have taken place thus far.

March 2, 1987	Research Review at M.I.T.
December 17, 1987	Research Review at M.I.T.

August 30, 1988	Research Review at M.I.T.
November, 1988	Information Exchange Meeting at Raytheon Corporation
March 24-25, 1989	External Technical Review at M.I.T.
September 25-26, 1989	Program Review at M.I.T.
March 15-16, 1990	Program Review at M.I.T.
October 10, 1990	Information Exchange Meeting at Harvard University

11.2 Workshops

Twice annually, subjects of interest are reviewed by CICS researchers and outside experts in the context of specialized, high level workshops. Listed below are the 12 workshops that have been held thus far:

October 22-24, 1986	Workshop on Distributed Algorithms in Communication and Computation
May 27-29, 1987	Workshop on Mathematical Aspects of Data Network Performance
November 21, 1987	Workshop in Computer Vision
June 14, 1988	Tutorial Workshop on Intelligent Control Systems (at the 1988 American Control Conference)
November 5, 1988	Workshop on Randomness in Computation
May 5, 1989	Machine Learning Workshop
May 10, 1989	Workshop on Image Analysis and Vision
November 12-14, 1989	Five Tutorials: Some Modern Applications of Mathematics
January 26, 1990	Workshop on Speech Processing and Recognition
May 15, 1990	Workshop on Global Models for Image Analysis
February 25, 1991	Workshop on VLSI and Computer Vision
April 1, 1991	Workshop on Analog, Neural and Asynchronous Computing

11.3 CICS Colloquia and Seminars

A series of monthly colloquia was initiated in February 1987. The series provides an opportunity for CICS researchers to interact with outstanding scholars whose work is related to ongoing research at the Center. Documented below the 29 colloquia that have taken place since the establishment of the Center. In addition, some 40 seminars have been held at MIT, Harvard University and Brown University.

February 1987
Professor Ulf Grenander
Brown University
"Can We Understand Shapes in Nature?"

March 1987
Professor Achi Brandt
Department of Mathematics
Weizmann Institute
"Fast Optimization and Fast Statistics"

May 1987
Dr. Shlomo Ta'asan
ICASE, NASA Langley Research Center
"A Multigrid Method for Slightly Indefinite Problems withApplication to the Riccati Equation"

October 1987
Professor Karl Johan Astrom
Lund Institute of Technology, Lund, Sweden
"Toward Intelligent Controllers"

December 1987
Professor Stephen Grossberg
Center for Adaptive Systems, Boston University
"Emergent Invariants of Neural Networks for Adaptive Pattern Recognition"

December 1987
Professor Robert Berwick
Artificial Intelligence Laboratory, M.I.T.
"Computation and Language Acquisition"

March 1988
Professor Persi Diaconis
Mathematics Department, Harvard University
"Projection Pursuit: An Approach to Visualizing in High Dimensions"

April 1988
Professor Brian D. Ripley
Department of Mathematics
University of Strathclyde, Glasgow
"Mathematical Morphology in Image Analysis"

May 1988
Professor Silvio Micali
M.I.T.
"Interactive Proofs, Zero-Knowledge and Applications"

October 1988
George N. Reeke, Jr.
The Neurosciences Institute and the Rockefeller University
"Selective Recognition Automata"

October 1988
Dr. M.K. Sparrow
Harvard University
"Topological Coding of Single Fingerprints"

October 1988
Professor J.L. Wyatt, Jr., M.I.T.
"Circuit Design Criteria for Stability in a Class of Lateral Inhibition Neural Networks"

November 1988
Professor Roger W. Brockett, CICS
"Differential Equations that Sort and Solve Linear Programming Problems"

November 1988
Dr. Michael Barnsley
Iterated Systems Inc. and
"Georgia Institute of Technology
Iterated Function Systems"

January 1989
Dr. J.L. Lions
College de France and Centre National des Etudes Spatiales
"Special Functionals for Distributed Systems"

March 1989
Professor R.T. Rockefellar
University of Washington, Seattle
"Extended Linear-Quadratic Programming and Large-Scale Optimization"

March 1989
Dr. Ingrid Daubechies
AT&T Bell Laboratories
"Wavelets: New and Old Results"

March 1989
Professor John S. Baras
Systems Research Center
University of Maryland
"Architectures for Real-Time Sequential Detection and Estimation"

1989
Professor Eugene Wong
University of California, Berkeley
"Stochastic Neural Networks"

October 1989
Nicolas Sourlas
Ecole Normale Superieure, Paris
"Spin-Glass Models and
Error-Correcting Codes"

November 1989
Bernard Gaveau
University of Paris VI
"Rate Constants for Meta-stable Systems"

December 1989
Stephane Mallat
New York University
"Complete Signal Representation
with Multiscale Edges"

February 1990
Frederick Jelinek
IBM T.J. Watson Research Center
"Language Translation by Statistical Methods"

March 1990
Michael Shub
IBM T.J. Watson Research Center
"P and NP in Various Contexts:
Hilbert's Nullstellensats and
Diophantine Equations"

October 1990
Y.Z. Ysypkin
Acacemy of Sciences, Moscow
"Control of Systems with Uncertainty:
Past, Present and Future"

October 1991
R.E. Kalman
Swiss Federal Institute of Tech., Zurich
"A New Look at Randomness as a
System Phenomenon"

November 1991
Shankar Sastry
University of California, Berkeley
"The Art (Control Theory) of Parking"

November 1991
Thomas Kailath
Stanford University, Stanford, CA
"Applications of Signal Processing and
Control to Semiconductor Processing"

December 1991
G. David Forney
Motorola based at Codex Corporation
"Dynamics of Linear Systems over Groups"

11.4 Honors, Awards and Invited Lectures

CICS Faculty at Brown University

Wendell Fleming
- Steele Prize of the American Mathematical Society, 1987.
- A special issue of the *SIAM Journal on Control and Optimization* will be dedicated to Wendell Fleming.

CICS Faculty at Harvard University

Roger Brockett
- 1989 Richard E. Bellman Control Heritage Award of the American Control Council, 1989.
- Elected to the National Academy of Engineering, 1991.

James J. Clark
- 1987 IEEE Acoustics, Speech, and Signal Processing Society Paper Award.

Y.C. Ho
- 1989 IEEE Field Award for Control Science and Engineering.
- Appointment to the Visiting Cockrell Family Regental Chair in Engineering at the University of Texas at Austin, 1988.
- Appointment to the T. Jefferson Coolidge Professorship of Applied Mathematics at Harvard University, 1988.
- Elected to the National Academy of Engineering, 1987.

Petros Maragos
- IEEE Acoustics, Speech and Signal Processing Society's Paper Award, 1988.
- National Science Foundation Presidential Young Investigator Award. 1987.

David Mumford
- MacArthur Fellowship, 1987.

Leslie Valiant
- Nevanlina Prize, 1986.

CICS Faculty at M.I.T.

Munther Dahleh
- George Axelby best paper award of the IEEE, April 1987.
- National Science Foundation Principal Young Investigator Award, 1991.

Robert Gallager
- IEEE Medal of Honor, 1989.
- Appointment to the Fujitsu Professorship of Electrical Engineering and Computer Science, M.I.T., 1988.

Shafi Goldwasser
- National Science Foundation Presidential Young Investigator Award, 1987.

Sanjoy Mitter
- Elected to the National Academy of Engineering, 1988.

Ronald Rivest
- Elected to the National Academy of Engineering, 1990.

Gunter Stein
- 1989 Bode Prize of the Control Systems Society.

John Tsitsiklis
- MIT's Edgerton Award for exceptional distinction in teaching, research and scholarship, 1989.
- National Science Foundation Principal Young Investigator Award, 1986.
- Control Systems Society Best Paper Award, 1986.

Alan Willsky
- Distinguished Member Award by the IEEE Control Systems Society, 1988.

Center Fellows and Research Assistants

Bonnie Berger
- Matchey Award for the best student paper, 30th IEEE Annual Symposium on the Foundations of Computer Science, 1990.
- 2-year NSF Mathematical Sciences Postdoctoral Research Fellowship

Cuneyt Ozveren
- Finalist in the 1989 IEEE CDC Best Paper Award Student Competition.

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1	Tsitsiklis, J.N.	P	On the Control of Discrete-Event Dynamical Systems	3/1/87
2	Tsitsiklis, J.N.	P	Decentralized Detection by a Large Number of Sensors	4/1/87
3	Gelfand, S.B.	TH Ph.D.	Analysis of Simulated Annealing Type Algorithms	5/1/87
4	Weiss, A.J. Willsky, A.S. Levy, B.C.	P	Maximum Likelihood Array Processing for the Estimation of Superimposed Signals	6/1/87
5	Chan, R.H. Strang, G.	P	The Asymptotic Toeplitz-Circulant Eigenvalue Problem	6/1/87
6	Weiss, A.J. Willsky, A.S. Levy, B.C.	P	Nonuniform Array Processing Via the Polynomial Approach	6/1/87
7	Weiss, A.J. Willsky. A.S. Levy, B.C.	P	Eigenstructure Approach for Array Processing with Unknown Intensity Coefficients	6/1/87
8	Borkar, V.S. Chari, R.T. Mitter, S.K.	P	Stochastic Quantization of Field Theory in Finite and Infinite Volume	7/1/87
9	Spinelli, J.M. Gallager, R.G.	P	Broadcasting Topology Information in Computer Networks	7/1/87
10	Weiss, A.J. Willsky, A.S. Levy, B.C.	P	Optimum and Suboptimum Array Processing for the Estimation of Superimposed Signals	7/1/87
11	Kuo, C.C.	TH Ph.D.	Discretiztion and Solution of Elliptic PDEs: A Transform Domain Approach	8/1/87
12	Ohta, Y. Tadmor, G. Mitter, S.K.	P	Sensitivity Reduction over a Frequency Band	8/1/87
13	Tseng, P. Bertsekas, D.P.	P	Relaxation Method for Linear Programs with Side Contraints	8/1/87
14	Tseng, P. Bertsekas, D.P.	P	Relaxation Methods for Monotropic Programs	8/1/89

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15	Humblet, P.A. Soloway, S.R.	P	A Fail-Safe Layer for Distributed Network Algorithms and Changing Topologies	5/1/87
16	Prince, J.L. Willsky, A.S.	P	Reconstructing Convex Sets from Support Line Measurements	9/1/87
17	Fleming, W.H. Souganidis, P.E.	P	Two-Player, Zero-Sum Differential Games	5/1/87
18	Geman, S.A. McClure, D.E.	P	Statistical Methods for Tomographic Image Reconstruction	6/1/87
19	Gidas, B.	P	A Renormalization Group Approach to Image Processing Problems	9/1/87
20	Gidas, B.	P	Parameter Estimation for Gibbs Distributions	11/1/87
21	Kushner, H.J. Dupuis, P.	P	Upper Bounds for Large Deviations for Nonsmooth Stochastic Difference Equations	2/1/87
22	Graffigne, C.	TH Ph.D.	Experiments in Texture Analysis and Segmentation	5/1/87
23	Grenander, U.	P	Statistical Inferences Made Possible by Advances in Computer Technology	5/1/87
24	Grenander, U.	P	Mathematics Motivated by Emergence of Different Kinds of Very Powerful Computers	9/1/87
25	Keenan, D.M. Grenander, U.	P	On the Shape of Planar Images	1/1/87
26	Kushner, H.J. Yin, G.	P	Asymptotic Properties of Distributed and Communicating Stochastic Approximation Algorithms	9/1/87
27	Kushner, H.J. Ramachandran, K.M.	P	Nearly Optimal Singular Controls for Wideband Noise Driven Systems	5/1/87
28	Glasserman, P.	P	Infinitesimal Perturbation Analysis of a Birth and Death Process	11/1/87
29	Ho, Y.C. Li, S.	P	Extensions of Infinitestimal Perturbation Analysis	11/1/89

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30	Strang, G.	P	A Framework for Equilibrium Equations	11/1/87
31	Brockett, R.W.	P	On the Computer Control of Movement	11/1/87
32	Kammen, D.M. Yuille, A.L.	P	Spontaneous Symmetry-Breaking Energy Functions and the Emergence of Orientation Selective Cortical Cells	11/1/87
33	Rossi, D.J. Willsky, A.S.	P	Object Shape Estimation from Tomographic Measurements - A Performance Analysis	11/11/87
34	Gallager, R.G.	P	Energy Limited Channels: Coding, Multiaccess, and Spread Spectrum	11/1/87
35	Chou, K.C.	TH S.M.	A Multi-Resolution Approach to an Inverse Conductivity Problem	12/1/87
36	Caromicoli, C.A.	TH S.M.	Time Scale Analysis Techniques for Flexible Manufacturing Systems	12/1/87
37	Tseng, P. Bertsekas, D.P.	P	Relaxation Methods for Problems with Strictly Convex Costs and Linear Inequality Constraints	11/1/87
38	Caromicoli, C.A. Willsky, A.S. Gershwin, S.B.	P	Multiple Time Scale Analysis of Manufacturing Systems	12/1/87
39	Prince, J.L. Willsky, A.S.	P	A Projection Space Map Method for Limited Angle Reconstruction	12/1/87
40	Mumford, D.	P	The Problem of Robust Shape Descriptors	12/1/87
41	Prince, J.L.	TH Ph.D.	Geometric Model-Based Estimation from Projections	1/1/88
42	Dahleh, M.A. Ohta, Y.	P	A Necessary and Sufficient Condition for Robust BIBO Stability	2/1/88
43	Dahleh, M.A. Ohta, Y.	P	L1 Sensitivity Minimization for Plants with Commensurate Delays	2/1/88
44	Feldman, P. Micali, S.	P	From Scratch to Byzantine Agreement in Constant Expected Time	2/1/88

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45	Chow, C.-S. Tsitsiklis, J.N.	P	An Optimal Multgrid Algorithm for Continuous State Discrete Time Stochastic Control	2/1/88
46	Rivest, R. Schapire, R.E.	P	Inference of Visible Simple Assignment Automata with Planned Experiments	10/1/87
47	Rivest, R. Schapire, R.E.	P	Diversity-Based Inference of Finite Automata	2/1/88
48	Rivest, R. Schapire, R.E.	P	A New Approach to Unsupervised Learning in Deterministic Environmentd	3/1/88
49	Rivest, R. Sloan, R.	P	A New Model for Inductive Inference	3/1/88
50	Rivest. R.	P	Learning Decision Lists	3/1/88
51	Quinlan, J.R. Rivest, R.L.	P	Inferring Decision Trees Using the Minimum Description Length Principle	3/1/88
52	Ozveren, C.M. Verghese, G.C. Willsky, A.S.	P	Asymptotic Orders of Reachability in Perturbed Linear Systems	3/1/88
53	Ho, Y.C.	P	Perturbation Analysis Explained	3/1/88
54	Geman, D. Geman, S.	P	Relaxation and Annealing with Constraints	3/1/88
55	Nikoukhah, R. Levy, B.C. Willsky, A.S.	P	Stability, Stochastic Stationarity and Generalized Lyapunov Equations for Two-Point Boundary-Value Descriptor Systems	3/1/88
56	Dahleh, M.A. Dahleh, M.	P	A Class of Adaptive Controllers with Application to Robust Adaptive Control	3/1/88
57	Dahleh, M.A. Meyer, D.G.	P	Time-Varying Compensation Can Yield No Improvement for *l* -Sensitivity Minimization	3/1/88
58	Chou, K.C. Willsky, A.S.	P	A Multi-Resolution, Probabilistic Approach to 2D Inverse Conductivity Problems	5/1/88
59	Bertsekas, D.P. Eckstein, J.	P	Dual Coordinate Ascent Methods for Linear Network FLow Problems	5/1/88

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61	Schapire, R.E.	TH S.M.	Diversity-Based Inference of Finite Automata	5/1/88
62	Sastry, S.S. Kokotovic, P.V.	P	Feedback Linearization in the Presence of Uncertainties	5/1/88
63	Richardson, T.J.	P	Existence Result for a Variational Problem Arising in Computer Vision	7/1/88
64	Tseng, P.	P	Relaxation Method for Large Scale Linear Programming Using Decomposition	7/1/88
65	Tseng, P.	P	Polynomial Time Algorithms for Finite Horizon, Stationary Markov Decision Processes	7/1/88
66	Tseng, P.	P	Dual Coordinate Ascent for Problems with Strictly Convex Costs and Linear Constraints: A Unified Approach	8/1/88
67	Eckstein, J.	P	The Lions-Mercier Splitting Algorithm and the Alternating Direction Method are Instances of the Proximal Point Algorithm	8/1/88
68	Mumford, D. Shah, J.	P	Optimal Approximations by Piecewise Smooth Functions and Associated Variational Problems	8/1/88
69	Nikoukhah, R. Levy, B.C. Willsky, A.S.	P	Stability, Stochastic Stationarity, and Generalized Lyapunov Equations for Two-Point Boundary-Value Descriptor Systems (Revised version of CICS-P-55)	7/1/88
70	Delyon, B.	P	On the Stability of Bilinear Stochastic Systems	8/1/88
71	Delyon, B.	P	Expansions for Determinants and for Characteristic Polynomials of Stochastic Matrices	8/1/88
72	Valiant, L.G.	P	Functionality in Neural Nets	8/1/88
73	Ehrenfeucht, A. Haussler, D. Kearns, M. Valiant, L.	P	A General Lower Bound on the Number of Examples Needed for Learning	8/1/88

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74	Rossi, D.J. Willsky, A.S. Spielman, D.M.	P	Object Shape Estimation from Tomographic Measurements - A Performance Analysis	8/1/88
75	Adams, M.B. Levy, B.C. Willsky, A.S,	P	Linear Estimation for 2-D Nearest-Neighbor Models	8/1/88
76	Gelfand, S.B. Mitter, S.K.	P	Simulated Annealing with Noisy or Imprecise Energy Measurements	8/1/88
77	Huber, P.J.	P	Spurious Structure? Or: Improved Bounds for the Kolmogorov Index	8/1/88
78	Delyon, B.	P	Convergence of the Simulated Annealing Algorithms	8/1/88
79	Borkar, V.S. Mitter, S.K.	P	Lattice Approximation in the Stochastic Quantization of (ϕ) Fields	8/1/88
80	Akra, M.A.	TH S.M.	On the Analysis of the Hopfield Network: A Geometric Approach	9/1/88
81	Bello, M.G. Willsky, A.S. Levy, B.C.	P	Construction and Applications of Discrete-Time Smoothing Error Models	9/1/88
82	Prince, J.L. Willsky, A.S.	P	Estimating Convex Shapes from Support Line Measurements Using Prior Geometric Information	10/1/88
83	Bertsekas, D.P. Tsitsiklis, J.N.	P	An Analysis of Stochastic Shortest Path Problems	10/1/88
84	Tseng, P.	P	A Simple Polynomial-Time Algorithm for Convex Quadratic Programming	10/1/88
85	Tseng, P.	P	A Very Simple Polynomial-Time Algorithm for Linear Programming	10/1/88
86	Ambrosio, L.	P	Variational Problems in SBV	10/1/88
87	Klein, P.N.	P	Efficient Parallel Algorithms for Planar, Chordal, and Interval Graphs	10/1/88

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88	Mitter, S.K.	P	Stochastic Quantization	11/1/88
89	Tseng, P.	P	Applications of a Splitting Algorithm to Decomposition in Convex Programming and Variational Inequalities	11/1/88
90	Bertsekas, D.P. Tsitsiklis, J.N.	P	Parallel and Distributed Iterative Algorithms: A Selective Survey	11/1/88
91	Tseng, P. Bertsekas, D.P. Tsitsiklis, J.N.	P	Partially Asynchronous, Parallel Algorithms for Network Flow and Other Problems	11/1/88
92	Tsitsiklis, J.N.	P	A Comparison of Jacobi and Gauss-Seidel Parallel Iterations	11/1/88
93	Ambrosio, L.	P	Existence Theory for a Class of Variational Problems	11/1/88
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