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<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Harvard University Division of Engineering & Applied Sciences Cambridge, MA 02138			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
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<b>13. ABSTRACT (Maximum 200 words)</b> This is the final report of F49620-95-1-0131 which ended on 12/31/97. Our motivation for the work reported here is the need for effective design, analysis, and optimization techniques for large, complex, stochastic Discrete Event Dynamic Systems (D, EDS). DEES are typified by communication networks, manufacturing, computer, C4I, traffic and other systems governed by human-made rules and clearly important in all aspects of modern technology. The two major research thrusts of this effort are: · New approaches to optimization specifically aimed at the problem of large search spaces that lack analytical structure. · New ways to simulate DEES in concurrent or parallel fashion that will speed up our ability to design and analyze their performance and that are naturally matched to emerging parallel computing capabilities and software paradigms such as object-oriented programming.				
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# FINAL REPORT

<b>AFOSR GRANT:</b>	F49620-95-1-0131
<b>TITLE:</b>	Optimization and Applications of Discrete Event and Hybrid Dynamic Systems

**REPORTING PERIOD:** 12/95-12/97

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## 1. OBJECTIVES

This is the final report of F49620-95-1-0131 which ended on 12/31/97. Our motivation for the work reported here is the need for effective design, analysis, and optimization techniques for large, complex, stochastic Discrete Event Dynamic Systems (DEDS). DEDS are typified by communication networks, manufacturing, computer, C<sup>4</sup>I, traffic and other systems governed by human-made rules and clearly important in all aspects of modern technology.

The two major research thrusts of this effort are:

- New approaches to optimization specifically aimed at the problem of large search spaces that lack analytical structure.
- New ways to simulate DEDS in concurrent or parallel fashion that will speed up our ability to design and analyze their performance and that are naturally matched to emerging parallel computing capabilities and software paradigms such as object-oriented programming.

Concrete research objectives we have pursued are:

1. Investigate basic issues related to these two thrusts in terms of feasibility and intrinsic limitations.
2. Explore new ways of solving complex discrete resource allocation problems that take explicit advantage of a DEDS structure.
3. Develop explicit algorithms that combine concurrent/parallel sample path construction techniques with optimization and study their properties
4. Apply the techniques we develop to some DEDS problems of practical interest. We are specifically targeting the study of a manufacturing system at the Wright-Patterson Air Force Base where new highly complex and computationally intensive processes for blade and rotor forging in jet engines are being developed. Over the past few months, we are also exploring other application areas of interest to the Air Force and attempting to establish contact with specific people and organizations we can collaborate with.

## 2. ACCOMPLISHMENTS/NEW FINDINGS

1. There exists a "universal" way to accomplish concurrent simulation for DEDS. Moreover, a specific scheme for doing so can be developed (termed "Time Warping Algorithm") and we have shown its application to a number of complex DEDS leading to significant speedup over conventional simulation.

- *Relationship to original goals:* this finding addresses a key issue contained in Objective 1 (see section 1). The development of the Time Warping Algorithm is also a crucial step in meeting Objective 3.

- *Relevance to AF mission and potential applications:* an efficient implementation of this "universal" concurrent simulation can revolutionize the field of discrete event simulation

used as a means for designing and improving the performance of technological systems in manufacturing, computer network, and C<sup>3</sup>I environments.

2. As stated in our research proposal, there exists a large number of human made system problems that have little analytical structure, lots of randomness, and a huge search space. Performance optimization of such systems is reduced to time-consuming simulation or ad hoc design. Our work on ordinal optimization opened up a new "softer" approach to these problems, namely, the tradeoff between getting "the best for sure" vs. "the good enough with high probability" is extremely favorable. Once we relax just a little bit on the quest for the "optimum", then much can be done for these "hard" problems. In particular, it is possible to develop a universally applicable and quantifiable set of rules which answer the following question:

**GIVEN :**

- i. a model of the system performance, however rough or crude,
- ii. an approximate idea of the magnitude of estimation errors of this model,
- iii. a rough idea about the design space, e.g. many good choices, many bad choices, mostly mediocre choices, etc.
- iv. the computation budget (the number of times one can afford to evaluate the model in (i))
- v. the required confidence in the answer (typically with probability 0.95)
- vi. definition of the "good enough", e.g. the top-n% of design

**QUESTION:**

*How many of the estimated top designs should we include in order to guarantee (w.p. 0.95) that at least k of the true top-n% design are in this group?*

It is possible to apply Ordinal Optimization (OO) to complex deterministic design problems while also addressing the non i.i.d. approximation error issue. Wright Patterson AFB IBR problem which was a major effort over the past year is fundamentally a deterministic but highly complex design problem. We used a much simpler and cruder IBR model to approximate the original complex finite element model. The theory of OO requires that these errors behave as i.i.d. noise. This is difficult to justify. The resultant research led us to a successful solution which consisted of

- Step 1: Use additional computation (but still much less than required by the full-fledge complex model solution) to do learning on the approximation errors.
- Step 2: Filter out the knowledge component learned in Step 1 above so that the residue approximation error is i.i.d.
- Step 3: Then we apply the OO procedure for selecting "good enough" designs.

This successful resolution also gives rise to two interesting theoretical issues on which research is currently continuing:

A. The relationship between Complexity and Randomness (see *An Introduction to Kolmogorov Complexity and Its Applications*, M. Li and P. Vitani, (2nd Edition) Springer, 1997).

B. The interplay between Learning and Computational Intelligence (see *Neuro-Fuzzy and Soft Computing: A Computational Approach to Learning and Machine Intelligence*,

J-S. R. Jang, C-T. Sun, and E. Mizutani, Prentice Hall , 1997).

- *Relationship to original goals:* Development of this set of universal answers for "narrowing down the search" is a fundamental foundational cornerstone of the ordinal optimization approach. We have made several theoretical advances which are in various stages of peer review

- *Relevance to AF mission and potential applications:* Although the above search rules have been tested on large academic problems successfully, the "proof of the pudding" is in the application of the results to a real world problem. To this end we have collaborated with the Material Directorate of WPAFB and the Ohio University successfully for a proof-of-concept experiment. This was reported at the 5/96 Electronic Prototype Manufacturing Meeting at WPAFB. Collaboration is continuing this coming year.

2. In a large class of DEDES, the problem of resource allocation is critical, especially in a dynamic environment. A new approach to adaptively allocate discrete resources in a stochastic setting is now fully developed and has been tested. We are currently in the process of rigorously establishing its properties and limitations.

- *Relationship to original goals:* this work is being pursued in the context of Objectives 2,3 (see section 1).

- *Relevance to AF mission and potential applications:* The problem of *discrete* resource allocation in a stochastic environment is a common one in practice and ranges from logistics and mobility issues to manufacturing and networking problems.

3. There exists a "universal" way to accomplish concurrent or parallel simulation for DEDES. This provides an answer to the basic question: is it possible to observe the behavior of a DEDES of arbitrary complexity under a set of operating conditions and be able to infer its behavior under any specified structural change (e.g., design parameter, system configuration)? Regardless of the complexity of the system, there exists a universal procedure for accomplishing this goal, based on a fundamentally different way of processing events. For a very broad class of DEDES (which includes the class of all Jackson-like queueing networks), it can be shown that this procedure is efficient and provides significant speedup over conventional simulation.

- *Relationship to original goals:* this finding addresses a key issue contained in Objective 1 (see section 1).

- *Relevance to AF mission and potential applications:* an efficient implementation of this "universal" concurrent or parallel simulation can revolutionize the field of discrete event simulation used as a means for designing and improving the performance of technological systems in manufacturing, computer network, and C<sup>3</sup>I environments.

### 3. PUBLICATIONS

• **Papers Published:**

- [1] Cassandras, C.G., "Optimal Policies for the 'Yield Learning' Problem in Manufacturing Systems", *IEEE Trans. on Automatic Control*, AC-41, 8, 1210-1214, 1996.
- [2] Bao, G., Cassandras, C.G., and Zazanis, M. "First and Second Derivative Estimators for Cyclic Closed Queueing Networks", *IEEE Trans. on Automatic Control*, AC-41, 8, 1106-1124 1996.
- [3] Vazquez-Abad, F.J., Cassandras, C.G., and Julka, V., "Centralized and Decentralized Asynchronous Optimization of Stochastic Discrete Event Systems", *Proc. 34th IEEE Conf. Decision and Control*, pp. 3632-3637, December 1995.
- [4] Cassandras, C.G., and Pan, J., "Some New Approaches to Discrete Stochastic Optimization Problems", *Proc. 34th IEEE Conf. Decision and Control*, pp. 573-578, December 1995.
- [5] Bao, G., and Cassandras, C.G., "A Rational Approximation Approach to Rare Event Probability Estimation for High-Performance Systems", *Proc. 34th IEEE Conf. Decision and Control*, pp. 865-870, December 1995.
- [6] Panayiotou, C., and Cassandras, C.G., "Optimization of Kanban-Based Production Systems", *Proc. of 1996 Intl. Workshop on Discrete Event Systems*, August 1996.
- [7] Z. B. Tang and Y.C. Ho "Modification of Adaptive Partitioned Random Search" *Proc. 1995 Conference on Decision and Control*,
- [8] Y.C. Ho, "On the Numerical solution of Stochastic Optimization Problems", *IEEE Trans. on Automatic Control*, 42, #5, 1997, pp. 727-729.
- [9] M.S. Yang, L.H. Lee, and Y.C. Ho, "On Stochastic Optimization and Its Applications to Manufacturing", *Lecture Notes in Applied Mathematics Series, Vol. 33*, pp. 317-331, 1997 (Proc. of AMS Conference on Stochastic Issues in Manufacturing, 1996).
- [10] Ho, Y.C., and Cassandras, C.G., "Perturbation Analysis for Control and Optimization of Queueing Systems: An Overview and the State of the Art", in "Frontiers in Queueing" (J. Dshalalow, Ed.), CRC Press, pp. 395-420, 1997.
- [11] E.T.W. Lau, and Y.C. Ho, "Universal Alignment Probabilities and Subset Selection for Ordinal Optimization", *J. of Optimization Theory and Applic.*, v.93, #3, pp. 455-490. 1997.
- [12] Cassandras, C.G., and Panayiotou, C., "Concurrent Sample Path Analysis of Discrete Event Systems", *Proc. of 35th IEEE Conf. Decision and Control*, pp. 3332-3337, December 1996.
- [13] Cassandras, C.G., and W. Shi, "Perturbation Analysis of Multiclass Multiobjective Queueing Systems with 'Quality-of-Service' Guarantees", *Proc. of 35th IEEE Conf. Decision and Control*, pp. 3322-3327, December

1996.

- [14] Pepyne D.L., and Cassandras, C.G., "Optimal Dispatching Control for Elevator Systems During Uppeak Traffic", *Proc. of 35th IEEE Conf. Decision and Control*, pp. 3837-3842, December 1996.
- [15] Panayiotou, C., and Cassandras, C.G., "Dynamic Resource Allocation in Discrete Event Systems", *Proc. of 5th IEEE Medit. Conference on New Directions in Control and Automation*, July 1997.
- [16] Y.C. Ho, "A Tutorial on Ordinal Optimization", *Proceedings of the Joint Conference on Information Sciences*, 1997.
- [17] L.H. Lee, E.T.W.Lau, and Y.C.Ho, "Explanation Of Goal Softening in Ordinal Optimization", *IEEE Trans. on Automatic Control*, 1997.
- [18] Y.C.Ho, "Review of the Book: Neuro-Fuzzy and Soft Computing" by Jang-Sun-Mizutani, *IEEE Trans. on Automatic Control*, 42, #9, 1997.
- [19] Pepyne, D.L., and Cassandras, C.G., "Optimal Dispatching Control for Elevator Systems During Uppeak Traffic", *IEEE Trans. on Control Systems Tech.*, 1997.
- [20] Cassandras, C.G., and Lafortune, S., "Discrete Event Systems: The State of the Art and New Directions", *Applied and Comput. Control, Signals, and Circuits*, 1997.
- [21] Pepyne, D.L., and Cassandras, C.G., "Design and Implementation of an Adaptive Dispatching Controller for Elevator Systems During Uppeak Traffic", *IEEE Trans. on Control Systems Tech.*, 1998.
- [22] Pepyne D.L., and Cassandras, C.G., "A Calculus of Variations Approach to the Optimal Control of Discrete Event Dynamic Systems", *36th IEEE Conf. Decision and Control*, December 1997.
- [23] Cassandras, C.G., Dai, L., and Panayiotou, C.G., "Ordinal Optimization for Deterministic and Stochastic Resource Allocation", *36th IEEE Conf. Decision and Control*, December 1997.
- [24] Cassandras, C.G., and Pepyne D.L., "Optimal Control of a Class of Hybrid Systems", *36th IEEE Conf. Decision and Control*, December 1997.

#### 4. PERSONNEL SUPPORTED

- Principal Investigators:

Yu-Chi Ho, Professor, Harvard University

Christos G. Cassandras, Professor, Boston University

• PostDoc:

Edward T.W.Lau, David Pepyne, Harvard University

• Graduate Students:

Mike Yang, J.T.Lee, X.C. Lin, Z.H. Chen, Harvard University

Kagan Gokbayrak, Rui Yu, Qinjia Liu, Boston University

## 5. INTERACTIONS/TRANSITIONS

### 6a. Participation/Presentations at Meetings, Conferences, Seminars

**C.G. Cassandras** gave invited (11) and contributed (4) talks at the following meetings/organizations:

- Chalmers University, Dept. of Automatic Control, Nov. 1995, Gothenburg, Sweden
- Northeastern University, Dept. of Electrical and Computer Engineering, Nov. 1995, Boston, MA
- Boston University, Dept. of Manufacturing Engineering, May 1996, Boston, MA
- University of California at Irvine, Dept. of Mechanical Engineering, June 1996, Irvine, CA
- *1995 European Control Conference*, Sept. 1995, Rome, Italy
- *Workshop on Verification and Control of Hybrid Systems*, October 1995, Rutgers U., NJ
- *34th IEEE Conference on Decision and Control*, Dec. 1995, New Orleans, LA
- *AIS'96 Conference*, April 1996, San Diego, CA
- *INFORMS Conference*, May 1996, Washington, DC
- *AMS-SIAM 1996 Workshop*, June 1996, Williamsburg, VA
- *13th IFAC World Congress*, July 1996, San Francisco, CA
- *1996 Intl. Workshop on Discrete Event Systems*, August 1996, Edimburgh, Scotland
- Workshop reviewing work on this grant, April 1996, Harvard U., MA
- *35th IEEE Conference on Decision and Control*, Kobe, Japan, December 1996
- *11th SPIE Intl. Symposium/Simulation Conference*, Orlando, FL, April 1997
- *5th IEEE Medit. Conference on New Directions in Control and Automation*, Paphos, Cyprus, July 1997.
- *9th INFORMS Applied Probability Conference*, Cambridge, MA, July 1997
- *6th Intl. Colloquium on Numerical Analysis and Computer Science with Applications*, Plenary Talk, Plovdiv, Bulgaria, August 1997.

**Y.C. Ho** gave invited talks at the following meetings/organizations

- Keynote address at Arizona State University System Center
- University of New Orleans
- 1995 Conference on Decision and Control
- Workshop reviewing work on this grant, April 1996, Harvard U., MA
- AMS Conference on Manufacturing, Williamsburg, VA
- ARO/NSF Conference on Communication Networks
- University of California at Davis, October 1996

- Berkeley Institute for Soft Computing, University of California at Berkeley, October 1996
- Politechnico of Torino, Short Course, November 1996
- *1997 Joint Conference on Information Sciences*, Keynote Speech, March 1997
- *11th SPIE Intl. Symposium/Simulation Conference*, Orlando, FL, April 1997
- Virginia Tech AFOSR Workshop, May 1997
- *World Congress on Intelligent Control and Automation*, Xian, PRC, June 1997
- *9th INFORMS Applied Probability Conference*, Cambridge, MA, July 1997

### **Consultative and Advisory Functions**

**Y.C. Ho:** National Academy of Engineering

#### **C.G. Cassandras:**

- Alphatech, Inc., Contact person: David Logan

### **Transitions**

- *Elevator dispatching control, OTIS Elevator Co.*

OTIS Elevator Co. is interested in new technologies for improving its dynamic dispatching control capabilities in large buildings with multiple elevators. These are large stochastic DEDS in which determining optimal dispatching policies is an intractable problem. Moreover, continuously changing operating conditions call for the capability to adjust dispatching policies depending on traffic load conditions. Techniques under investigation in this project have been adopted by OTIS in planning their next generation of elevator dispatchers. Dr. Bruce Powell, OTIS Elevator Co., has worked closely with C.G. Cassandras in this effort.

- *Design and analysis of packet radio networks, Naval Research Laboratory.*

The Naval Research Laboratory (NRL) is studying new methods for designing and controlling voice/data integration mechanism in packet radio networks. Techniques for concurrent and parallel simulation as well as ordinal optimization have been adopted by NRL personnel in their work and results reported in journals and conferences.

Contact person: Dr. Jeffrey Wieselthier has worked closely with C.G. Cassandras in this effort. He has also interacted with Y.C. Ho on issues related to ordinal optimization.

- *Visit to Ohio State University and the Material Laboratory of WPAFB*

During April and May 1996, Y.C. Ho and a student were present at meetings among WAFB, OU, and VPI personnel to discuss the Integrated Turbine Blade Forging Problem and conducted successfully a proof-of-concept experiment to validate the OU model.

- *Ordinal Optimization for the Integrally Bladed Rotor (BR) manufacturing problem, Wright-Patterson Air Force Base. Contact person: Dr. Jim Malas, WPAFB.*

- *Participation in workshop sponsored by the army research office and nsf at William and Mary College, June 27-28 1996 for Mathematical Issues of Stochastic*

Manufacturing

Airlie House, VA August 9-10, 1996 Control and optimization Issues in Communication networks

## **6. NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES**

None over the reporting period.

## **7. HONORS/AWARDS**

**Y.C.Ho** (Lifetime):

Guggenheim Fellow (1970), Fellow of IEEE (1972), Distinguished Member of IEEE Control System Society (1985), Member of National Academy of Engineering (1987), IEEE Control Science and Engineering Field Award (1989), Chiang Technology Achievement Prize (1993). became a Life Fellow of IEEE in 1997

**C.G. Cassandras** (Lifetime):

Lilly Fellow (1991), Fellow of IEEE (1996), IFAC Harold Chestnut Prize (1999)  
**C.G. Cassandras** elected Fellow of IEEE, Dec. 1995.