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The research resulted in major improvements in Markov models to be used in Monte Carlo modeling of reliability problems. These include a number of component dependency models and modeling of unrevealed failures. A new sampling technique, the method of self-transitions, is developed for treating time dependent failure rates, and non Markovian generalizations are made to model replacement of ageing parts and as-good-as-new repair.

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Monte Carlo reliability Analysis

FINAL REPORT, AFOSR - 84 - 0340

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INTRODUCTION

A final report on the accomplishments of the research contract AFOSR - 84 - 0340 is contained in the following paragraphs. The exploratory research leading to the initiation of the contract in September, 1984 is first reviewed in order to put the accomplishments of the contract period into perspective. A description of the work carried out under AFOSR sponsorship is then presented, and the continuing work since the end of the contract is outlined. The personnel associated with the contract, and the publications and appearances resulting from the research are listed.

RESEARCH PRIOR TO SEPTEMBER, 1984

The research carried out in Monte Carlo Reliability Analysis during the four year period during which support was provided by AFOSR was made possible by earlier work carried out by the principal investigator and his students to establish the viability of Monte Carlo simulations for system reliability problems. The earlier work established that Monte Carlo methods could be employed effectively to estimate mission reliability for complex systems in which highly redundant configurations assured very small system failure probabilities.

As in other Monte Carlo simulations, the system configuration was represented by a fault tree. In contrast to other work, however, the fault tree was then represented as a set of continuous time Markov equations, and the simulation was carried out in a Lagrangian fashion. This resulted in a great improvement in computational efficiency over previous methods when highly reliable systems were considered. For in traditional methods an N component system would require a sampling of the time-to-failure of each of the N components in each of independent trials, even though failures rarely occurred during the mission time. In the Lagrangian approach only one or at most a few samplings per trial are required, thus greatly decreasing the time per trial.

Even with the speed-up resulting from the Lagrangian approach, computing times for the simulation of highly reliable systems could still be prohibitive. For with the binomial sampling used in analog Monte Carlo calculations, many millions of histories were sometimes required to achieve sufficiently small variances in the system failure probability. This problem was circumvented by the invention variance reduction techniques that are forms of importance sampling; these greatly reduced the number of required trials. These variance reduction techniques are referred to as forced transitions, in which the frequency of faults is artificially increased, and failure biasing, in which the ratio of failure to repair rates is artificially increased. The net effect of the employment of these techniques was an increase in computational efficiency of well over one thousand without introduction of bias into the reliability estimator.

RESEARCH FROM SEPTEMBER 1984 TO DECEMBER 1988

As a result of the high computational efficiencies achieved in the foregoing work, relatively little effort has been expended to further increase computational efficiency through the use of additional variance reduction devices. In contrast, the predominant thrust of the research during the period of AFOSR support has been toward developing Monte Carlo methods capable of treating more realistic system models.

During the initial phase of the AFOSR work a tally was developed to estimate system availability along with the system reliability.[1] In addition computational efficiency was increased to very large fault trees by incorporating bottom up evaluation of the fault tree logic as an alternative to the use of minimum cut sets. The primary emphasis however was placed on the simulation of component dependency models. Before the beginning of AFOSR research the Markov equations were utilized only to model systems of components with independent failure characteristics - an unnecessary restriction.

Three classes of dependency models were developed: (1) standby configurations, in which a primary component must fail before its backup may fail (2) shared load configurations in which the failure of one component would cause increased failure rates in one or more other components, and (3) shared repair crew components, where simultaneous repairs could not be undertaken on all failure components. These models and some elaborations of them were incorporated into the Monte Carlo modeling capability in such a way that they did not adversely effect the previously mentioned variance reduction methods. The results of these studies are presented in References 2 and 3.

While the foregoing work allowed the treatment of fairly general dependency models, the Monte Carlo simulation was still restricted to components with constant failure rates (i.e. exponential distributions of time-to-failure). In order to treat components with more realistic time-dependent failure rates that incorporated the wear and infant mortality effects of the familiar "bathtub curve", it was necessary to generalize the Monte Carlo simulation to include inhomogeneous Markov equations. Two sampling techniques were formulated for this purpose: mode sampling, and the method of self-transitions. While both methods were shown to be unbiased and to be compatible with the variance reduction techniques, the self transition technique was shown to be superior from the standpoint of computational efficiency. Further study of mode sampling was therefore dropped. The method of self transitions, which in effect converts the the inhomogeneous Markov equations into a pseudo semiMarkov process with time-independent total transition rates, was incorporated into all further transitions. This work is reported in Reference 4.

Along with the incorporation of time-dependent failure rates, the distinction was made between revealed and unrevealed failures: while a revealed failure is immediately apparent and can be fixed, an unrevealed failure causes the component to remain in a failed state until a periodic replacement is made thus restoring components to as-good-as-new at predetermined time intervals. Such unrevealed failures can be modeled in terms of inhomogeneous Markov equations. Likewise the revealed failures may be treated at inhomogeneous Markov equations, provided that the aging is allowed to continue through the short repair intervals (a very minor approximation) and more significantly, that the repairs when made are as good as old, that is they do not change in instantaneous failure rate of the component. The incorporation of these models into Monte Carlo simulation in which our variance reductions techniques are also used is presented in Reference 4.

Strictly speaking, the inhomogeneous Markov processes cannot model parts replacement of components with time-dependent failure rates unless those replacements take place at predetermined and unalterable time intervals. Thus, replacement upon failure and as-good-as-new component repair cannot be modeled. Neither can preventive maintenance be modeled if strategies based on replacing components after a fixed lifetime are to be employed. For these reasons, the Monte Carlo formulation was generalized to treat limited classes of nonMarkovian problems where the transition probabilities depended not only on the state of the system and the clock time, but also of the times since the replacements of each of the system components. This generalization was a powerful tool for treating problems thar include preventive maintenance and replacement of worn parts. The methodology and its application is presented in Reference 5.

It has long been argued that one of the advantages of deterministic calculations is that they provide curves of reliability and availability vs time and these provide insight that the single point results of Monte Carlo calculations cannot. One unanticipated area in which the usefulness of Monte Carlo reliability simulation was significantly improved was in the development of tallying procedures that allowed plots to be generated of reliability and interval availability vs time from Monte Carlo calculations. The techniques for graphing Monte Carlo reliability results are presented in Reference 6 and employed in subsequent papers.

During the last year of AFOSR support, attention was focused on applying the foregoing methodology to the realistic modeling of increasingly realistic computer and aerospace control systems on the one hand, and to the study of the effects of mechanical loading on time dependent failure rates on the other. In the modeling effort 2/3 voting systems with spares were first studied to examine the relative importance of spares exhaustion and fault handling errors. The first published work related to this study is contained in Reference 7. More recently, comparisons are being made between the Monte Carlo Methods developed under AFOSR sponsorship and the deterministic reliability simulation methods contained in the NASA code HARP. The comparisons are not complete. However, to date the value of Markov Monte Carlo methods seems to be significant. In a benchmark jet engine controller problems with 20 components and more than 200 minimum cut sets, the Monte Carlo calculations required 20 minutes on a VAX computer while the deterministic calculation required more than 10 hours. NonMarkovian generalizations to the problem cannot be treated by the HARP code. This work will be documented in a invited paper for presentation by the principal investigator at the 1989 Winter Simulation Conference, to be held in Washington D. C.

Along with the foregoing system modeling studies an effort was made to relate failure rate data used in systems modeling to mechanical loading characteristics. Focus has been on understanding the distributions of time to failure that result from fatigue of brittle components. Stress-strain interference theory is cast in a form which gives rise to distributions of delayed fracture in brittle components, particularly ceramics. The initial stages of this work are reported in Reference 9. The work has continued since the termination of AFOSR funding. Ceramic components are found to give rise to Weibull distributions that correspond to decreasing failure rates. At present it appears that the Weibull modulus is closely related to the material properties, but nearly independent of the stress magnitude, and the geometry of the component. Conversely the Weibull scale parameter is a strong function of stress and geometry. This work is still in progress without external funding and will be published when the fundamental relations are established between failure rates, loads and material properties.

PERSONNEL

In addition to the principal investigator, E. E. Lewis, a number of graduate students in the Department of Mechanical Engineering at Northwestern University were associated with the AFOSR sponsored research. Laura Olvey was supported for approximately one year on the grant and was responsible for the work on unavailability analysis. Following completion of her masters degree, Ms Olvey chose do her doctoral research in another area of Mechanical Engineering; she recently completed her doctoral thesis in Mechanical Engineering at Northwestern. Mr. Franz Boehm was supported for approximately three years by the AFOSR grant and should complete his doctoral thesis this spring. Mr. Boehm has been active in all aspects of the work described above with his dissertation being focused on the problem of using stress-strength interference theory for deriving distributions of time-to-failure for brittle mechanical components.

In addition to Ms. Olvey and Mr. Boehm, four other people have taken part in the Monte Carlo reliability research. However, no AFOSR funds have been used to support them. They are Z. Tu, C. Kirsch and B. Kelkoff. Z. Tu was a visiting scholar from China for two years in the Department of Mechanical Engineering. C. Kirsch and U. Hald were exchange students each visiting Northwestern University for one year from the University of Stuttgart. Ms. Kelkoff was a M. S. student attending Northwestern part time while employed at AT&T Laboratories; she has recently completed the requirements for the M. S. Degree.

PUBLICATIONS

The nine references listed below are the result entirely or in part of the AFOSR grant. Reprints of these have been sent to AFOSR either separately or as appendices to annual progress reports.

APPEARANCES

The AFOSR research as been reported at meeting and seminars on eleven different occasions. They are the following:

E. E. Lewis, "Monte Carlo Unavailability Analysis," Amer. Nucl. Soc. National Meeting, Washington, D.C., Nov. 15, 1984.

E. E. Lewis, "Markov Monte Carlo Reliability Analysis," AFOSR Reliability Workshop, Luray, Virginia, May 30, 1985.

E. E. Lewis, "Component Dependency Modeling in Markov Monte Carlo Calculations," Amer. Nucl. Soc. National Meeting, Boston, June 12, 1985.

E. E. Lewis, "Monte Carlo Simulation of Reliability Problems," ASME Pressure Vessel & Piping Conf., New Orleans, June 24, 1985.

E. E. Lewis, "Monte Carlo Evaluation of Fault Trees," Colloquium, School of Nuclear Engineering, Purdue University, April 8, 1986.

E. E. Lewis, "Monte Carlo Reliability Analysis," Faculty Luncheon Seminar Series, Department of Mechanical and Nuclear Engineering, Northwestern University, April 29, 1986.

E. E. Lewis, "Monte Carlo Methods for Reliability Analysis," Seminar Rome Air Development Center, Griffiss Air Force Base, New York, Dec. 15, 1986.

E. E. Lewis, "Generalization of Markov-Monte Carlo Reliability Analysis to Include Non-Markovian Maintenance Strategies," Int. Topical Conf. Probabilistic Safety Assessment and Risk Management, Zurich, Sept. 2, 1987,

E. E. Lewis, "Parts Renewal in Continuous-Time Monte Carlo Reliability Simulation," Am. Nucl. Soc. National Meeting, Los Angeles, Nov. 22. 1988

E. E. Lewis, "Monte Carlo Reliability Analysis," Seminar, NASA Langley Laboratory , March 24, 1988

F. Boehm , "Parts Renewal in Continuous-Time Monte Carlo Reliability Simulation," 1988 Reliability and Maintainability Symposium, Los Angeles, Jan 24, 1988

REFERENCES

(1) E. E. Lewis and L. Olvey, "Monte Carlo Unavailability Analysis," Trans. Am. Nucl. Soc. 47, 329 (1984).

(2) E. E. Lewis and Z. Tu, "Monte Carlo Simulation of Reliability Problems," Proc. ASME Pressure Vessel & Piping Conf., PVP-Vol. 98-5, New Orleans, June 24-26, 1985.

(3) E. E. Lewis and Z. Tu, "Component Dependency Modeling in Markov Monte Carlo Calculations," Trans. Am. Nucl. Soc. 49, 287 (1985).

(4) E. E. Lewis and Z. Tu, "Monte Carlo Modeling by Inhomogeneous Markov Processes," Reliability Engr. 16, 277-296 (1986).

(5) E. E. Lewis, F. Boehm, U. P. Hald & Z. Tu "Generalization of Markov-Monte Carlo Reliability Analysis to Include Non-Markovian Maintenance Strategies," Proc. Int. Topical Conf. Probabilistic Safety Assessment and Risk Management, Zurich, Aug. 30-Sept. 4, 1987, Verlag TUV Rheinland, 1987.

(6) E. E. Lewis, Z. Tu, U. P. Hald and F. Boehm, "Explicit Time-Dependent Analysis in Monte Carlo Reliability Simulations," Trans. Am. Nucl. Soc. 55, 443-444 (1987).

(8) F. Boehm, U. P. Hald and E. E. Lewis, "Parts Renewal in Continuous-Time Monte Carlo Reliability Simulation," Proc. 1988 Reliability and Maintainability Symposium, Jan. 21-28, 1988, Los Angeles, pp. 345-349.

(9) F. Boehm and E. E. Lewis, "A Stess-Strength Interference Methodology for Ceramic Component Reliability Analysis," to appear in Computational Mechanics of Probabilistic and Reliability Analysis, W. K. Liu & T. Belytschko (eds.) Elme Press Int., 1989