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13. ABSTRACT (Maximum 200 words) The major areas of research originally proposed for study included: <ul style="list-style-type: none"> Estimating the marginal contribution of a force component to the overall performance of that force, when the latter can be measured only indirectly, for example by combat simulations using entities such as JANUS or CASTFOREM. Such estimates can then be used to help in optimally allocating a budget to produce the best force performance. Incorporating action over time into the stochastic scenario analysis methodology now in use by the U. S. Army TRADOC Analysis Center, to create a dynamic scenario analysis methodology that can be applied to force design and analysis. Improving solution methods for variational inequalities and related generalized equations, and applying the improved methods to the solution of problems arising in modeling efforts such as those just mentioned. A subsequent modification proposal added additional research in the first of these three major topic areas. This additional research was in the area of attrition calibration and the coupling of models performing at different scales, with application to the evaluation and prediction of effectiveness.				
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Final Progress Report

For period 1 August 1997 – 31 July 2002

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University of Wisconsin-Madison

27 October 2002

1 Statement of the problem studied

The major areas of research originally proposed for study included:

- Estimating the marginal contribution of a force component to the overall performance of that force, when the latter can be measured only indirectly, for example by combat simulations using entities such as JANUS or CASTFOREM. Such estimates can then be used to help in optimally allocating a budget to produce the best force performance.
- Incorporating action over time into the stochastic scenario analysis methodology now in use by the U. S. Army TRADOC Analysis Center, to create a dynamic scenario analysis methodology that can be applied to force design and analysis.
- Improving solution methods for variational inequalities and related generalized equations, and applying the improved methods to the solution of problems arising in modeling efforts such as those just mentioned.

A subsequent modification proposal added additional research in the first of these three major topic areas. This additional research was in the area of attrition calibration and the coupling of models performing at different scales, with application to the evaluation and prediction of effectiveness.

2 Summary of the most important results

This section summarizes the work done under the grant. It is organized chronologically, explaining major results achieved during each time period during which the grant was active.

From inception of the grant to the end of 1998, the technical results achieved were in two main areas: (1) deterministic and stochastic models to support military decision-making, and (2) mathematical tools for numerical solution of variational inequalities and optimization problems, especially those arising from the models in (1).

The primary effort in models for supporting decision-making was undertaken in collaboration with the U. S. Army Center for Army Analysis (CAA), represented by Mr. Gerald Cooper. CAA is concerned with improving the performance of the combat models they use, and in particular with enhancement of a calibration model called ATCAL. This model is used as a bridge for extrapolating results computed using high-resolution models for use with larger-scale, low-resolution models employed to evaluate actions at the theater level. A part of the work done by ATCAL is extrapolation of the results of fires (both direct and indirect) to the environment of the larger model. CAA believed that some of the ways in which ATCAL does this extrapolation needed improvement, particularly for the case of indirect (area) fire.

An important part of the required improvement pertained to the mechanism for determining importance (value) of target categories. The version of ATCAL then current used a nonlinear formula that seems to have been devised as an approximation to the

eigenvalue weight (linear weight) method for assigning values, but for which an underlying theoretical justification seems not to exist. The approximation was originally introduced as an expedient to reduce the instability exhibited by the linear weights.

Under previous Army sponsorship the PI developed an extension of the linear weight analysis and provided theoretical justification by showing that the values calculated in this manner are actually shadow prices of mathematical programming problems. This work was published in [1,2] (references here and elsewhere are to the bibliography in Section 6). One of the tasks pursued was adaptation of this methodology in support of CAA, particularly in the improvement of ATCAL. The new methodology was based on Nash equilibrium, which led to variational inequality formulations. The PI furnished an interim report to Mr. Cooper of CAA in July 1998 giving more detail on this adaptation.

A considerable amount of computational work was done under this grant to investigate the extent of difference between importance weights produced by the current ATCAL procedure and those produced by the shadow-price methodology mentioned above. Substantial differences were found when using a sample data set provided by CAA. The PI presented a briefing on these results to Mr. Cooper and others at CAA in December 1998.

During the PI's December 1998 visit to CAA, an area of concern to CAA was identified. Briefly, this concerns the behavior of ATCAL when it is run with decreased unit frontages. The results did not appear to scale as one would normally expect. Mr. Cooper identified some questions in this area, and the PI began an effort to examine these in order to determine whether this scaling behavior reflected problems with the underlying ATCAL model or whether it had some other explanation. This effort continued into calendar year 1999.

Another area of effort in models to support military decision making came as a result of an invitation from ARO for the PI to give a plenary lecture at the Army Conference on Applied Statistics, held in Las Cruces, NM in October 1998. The lecture, given jointly with Richard R. Laferriere of the U. S. Army TRADOC Analysis Center, White Sands Missile Range, NM, later developed into a paper [6] published in the proceedings of the conference. Mr. Laferriere and the PI revised this paper into a publication in *Phalanx* [7], which in 2001 won the John K. Walker Jr. Award of the Military Operations Research Society.

Also during this reporting period, progress was made on the line of research involving development of new mathematical tools for the formulation and solution of variational inequalities. In particular, the general methodology previously developed under ARO sponsorship in the paper [2] was applied to several specific classes of variational inequality problems to produce solution methods that take advantage of the problems' structure. This work was written up in the proceedings paper later published as [8]. It also formed the core of an invited plenary lecture given by the PI to the 1998 Fall National Meeting of the Institute for Operations Research and the Management Sciences (INFORMS) in October 1998. In addition, a paper [4] sponsored by this grant developed

a special application of composition duality that later resulted in a significant computational advance (see description below in section for calendar year 2000).

Technical results achieved during calendar year 1999 were in two main areas: deterministic and stochastic models to support military decision-making, and mathematical tools for numerical solution of variational inequalities and optimization problems, especially those arising from the military decision-making models.

In terms of time devoted to the research effort, the largest fraction of the effort went to investigating the ATCAL attrition calibration code provided by CAA. As noted above, Mr. Gerald Cooper of CAA had noted discrepancies in the results given by ATCAL when unit frontages were rescaled, and he asked if we could help explain these. In an effort to do so, two assistants (P. Ranavat and H. Sellami) undertook an analysis, verification, and commenting of the complete two-phase ATCAL code provided by CAA. Significant discrepancies were found, and a report describing these was provided to CAA (Mr. Gerald Cooper) in May 1999. Subsequent correspondence with CAA indicated that at least some of these discrepancies were the result of different versions of the ATCAL code that existed at CAA. The commented code was provided to CAA (Dr. Kosmo Tatalias) in June 1999.

The next-largest fraction of time was also devoted to another software effort, this time connected to the homotopy code for solving variational inequalities previously prepared with ARO support. During the summer of 1999 this code was extensively revised and its usefulness was extended. A user's manual was also prepared, written by Ms. K. Akey under supervision of the PI.

The reason for undertaking this task at that point in time was that this homotopy code provides a convenient way to solve variational inequalities with general polyhedral constraint sets. This is in contrast to the most popular solver now on the market, the PATH solver embedded in the GAMS modeling language, as the latter can solve only problems whose sets are not only polyhedral but in fact are "boxes" (rectangular sets in n -dimensional space). In order for this code to solve other problems, their constraints have to be converted to the box form by adding multipliers, generally at the cost of a substantial increase in the dimensionality of the problem. Problems already encountered in the combat modeling phase of this research effort included variational inequalities whose underlying sets are not rectangular and on which the PATH solver did not produce good results. The homotopy code can provide a way of solving such problems.

The third major area in which progress was made in 1999 was that of composition duality. This is a general method for generating dual problems from multifunction inclusions, including variational inequalities and optimization problems. It contains many previous duality schemes, including the very well known perturbational duality scheme of Rockafellar for convex optimization, as special cases. The general scheme was laid out and justified in [5], and some applications to the exploitation of special structure in variational inequalities were developed in [8]. As an example of the generality of this method, it can be pointed out that the method includes not only known duality schemes

from optimization, but also methods from other fields such as the “tearing” method of Gabriel Kron for solving electrical network problems.

The technical results achieved in calendar year 2000 were principally in mathematical analysis of variational inequalities and optimization problems. These include problems arising from the military decision-making models.

The major methodological area covered by work in 2000 was that of composition duality. Additional applications to the exploitation of special structure in variational inequalities were developed and published; see [9]. The work done during this phase represented the second step of the development process. The first step had established the broad outline of the methodology, along with some applications. This phase therefore involved developing applications of the composition duality structure to specific problems, notably in computational solution of variational inequalities, testing these, and documenting the results.

A considerable computational advance in solving structured complementarity problems resulted from an application of the 1998 paper [4], sponsored by this grant. Using the methods of that paper, Michael Ferris and Todd Munson developed in [10] a “preprocessing” method for large mixed complementarity problems. This method automatically exploits the structure of the problem, together with the results in the paper just mentioned, to reduce the size of the problem before it is sent to a solver for numerical solution. After the reduced model is solved, the preprocessor recovers the solution of the original model from that of the reduced form. As an example of what it can do, when the preprocessor was applied to a large equilibrium model of Chavas and Cox for simulating trade liberalization in the dairy industry it reduced the problem from 46,123 variables to 13,655 (a reduction of more than 70%).

In calendar year 2001 and in the part of 2002 included in the period of performance, most of the effort concentrated on variational problems and on methods for efficiently improving or optimizing stochastic networks. This latter area is an outgrowth of the second major work area originally proposed, that of handling action over time in stochastic optimization.

The paper [13] identifies a phenomenon occurring in the numerical solution of variational inequalities, in which an iterative procedure may appear to have converged even if it is not close to a solution of the problem, and in fact even if no solution exists at all. This phenomenon can occur even with good (superlinearly convergent) numerical methods, whereas the corresponding situation in the case of ordinary nonlinear equations does not. Thus, this illustrates a situation in which the transition from equations to the more general case of variational inequalities introduces a genuinely new type of behavior.

The paper [15] shows how to extend a known procedure [3] for sensitivity analysis of variational inequalities posed over polyhedral convex sets, developed by the author under a predecessor ARO grant, to the much more general situation of a variational condition posed over a set defined by finitely many smooth nonlinear inequalities and equations.

This methodology permits one to predict the existence of a locally unique solution that is stable under small perturbations of the constraints and of the function in the variational condition. In fact this solution is a Lipschitzian function of those perturbations and is actually B-differentiable at the “base point” (unperturbed problem). The method provides an explicit formula for computing the B-derivative in terms of the original problem functions and their derivatives. These results represent the strongest sensitivity analysis methods for this class of problems now known to the author.

The papers [12,14] and the Army Operations Research Symposium presentation [11] describe work on a new method for improvement or optimization of stochastic networks. One of the most useful tools in analyzing such systems is stochastic simulation, but if one wants to improve the system, rather than just to predict its performance “as-is,” then repeated simulations are usually necessary. If the system is complex, these simulations often require long running times, and therefore such analyses can require very large amounts of time. We have developed an experimental method using a two-phase approach, with the aim of improving or optimizing the network in much less time. The first phase uses stochastic network approximations in place of repeated simulations to predict good ways to improve the network’s performance, while the second phase uses one simulation run to validate the predicted improvement. Preliminary tests have shown good improvement capability, with a very substantial reduction in running times compared to standard repeated simulation methods.

3 Listing of all publications and technical reports supported under this grant or contract

3.1 *Papers published in peer-reviewed journals*

1. S. M. Robinson, A reduction method for variational inequalities. *Mathematical Programming* **80** (1998) 161 – 169
2. S. M. Robinson, Composition duality and maximal monotonicity. *Mathematical Programming* **85** (1999) 1 – 13
3. S. M. Robinson, Linear convergence of epsilon-subgradient descent methods for a class of convex functions. *Mathematical Programming* **86** (1999) 41 – 50

3.2 *Papers published in non-peer-reviewed journals or in conference proceedings*

4. R. R. Laferriere and S. M. Robinson, Scenario analysis in U. S. Army decision making. In: B. A. Bodt, ed., *Proceedings of the Fourth Annual U.S. Army Conference on Applied Statistics, 21-23 October 1998*, pp. 11-16. U. S. Army Research Laboratory Report ARL-SR-84, November 1999
5. S. M. Robinson, Structural methods in the solution of variational inequalities. In: G. Di Pillo and F. Giannessi, eds., *Nonlinear Optimization and Related Topics*, pp. 369 – 380. Kluwer Academic Publishers, Dordrecht, 2000
6. R. R. Laferriere and S. M. Robinson, Scenario analysis in U. S. Army decision making, (Extensively revised version of paper numbered 4 just above) *Phalanx* **33**, No. 1 (2000) pp. 10 ff.

7. S. M. Robinson, Generalized duality in variational analysis. In: N. Hadjisavvas and P. Pardalos, eds., *Advances in Convex Analysis and Global Optimization*, pp. 205 – 219. Kluwer Academic Publishers, Dordrecht, 2001
8. J. Granger, A. Krishnamurthy, and S. M. Robinson, Stochastic modeling of airlift operations, in: B. A. Peters, J. S. Smith, D. J. Medeiros, and M. W. Rohrer, eds., *Proceedings of the 2001 Winter Simulation Conference*, pp. 432 – 440

3.3 Papers presented at meetings, but not published in conference proceedings

9. J. Granger, A. Krishnamurthy, and S. M. Robinson, Fast improvement of simulated networks, 2001 U. S. Army Operations Research Symposium, October 2001

3.4 Manuscripts submitted, but not published

10. S. M. Robinson, False numerical convergence in some generalized Newton methods, 2001, accepted for publication in *Equilibrium Problems and Variational Models*, Eds. P. Daniele, F. Giannessi and A. Maugeri, Kluwer Academic Publishers, Dordrecht, 2003
11. J. Granger, A. Krishnamurthy, and S. M. Robinson, Approximation and optimization for stochastic networks, 2002, submitted for publication to Proceedings of the Workshop on Dynamic Stochastic Optimization, held in March 2002 at the International Institute for Applied Systems Analysis, Laxenburg, Austria; proceedings to be published by Springer-Verlag
12. S. M. Robinson, Constraint nondegeneracy in variational analysis, 2002, submitted to *Mathematics of Operations Research*
13. S. M. Robinson, A Linearization Method for Nondegenerate Variational Conditions, 2002, submitted for publication to Proceedings of the special session on variational analysis at the Joint Meeting of the American Mathematical Society and Unione Matematica Italiana, held in Pisa, Italy, June 2002; to be published in the *Journal of Global Optimization*

3.5 Technical reports submitted to ARO

No technical reports were submitted to ARO under this grant.

4 List of all participating scientific personnel showing any advanced degrees earned by them while employed on the project

1. Kristen M. Akey. Ms. Akey was an undergraduate student during her work with this project. She received the degree of Bachelor of Science – Industrial Engineering in December 1999, continued as a graduate student, and according to records in this department she completed the requirements for the degree of Master of Science – Industrial Engineering as of December 2000.
2. Mert C. Demir, Research Assistant. He received the degree of Doctor of Philosophy (Industrial Engineering) in 2000.
3. Prashant R. Ranavat, Research Assistant. He received the degree of Master of Science, Industrial Engineering in 1999.

4. Stephen M. Robinson, Professor
5. Hichem Sellami, Research Assistant. He received the degree of Master of Science, Computer Sciences, in 1999.
6. Yi-Chun Tsai, Research Assistant

5 Report of Inventions (by title only)

There were no reportable inventions during the period of this grant.

6 Bibliography

1. S. M. Robinson, Shadow prices for measures of effectiveness, I: Linear model. *Operations Research* **41** (1993) 518 – 535; Erratum, *Operations Research* **48** (2000) 185
2. S. M. Robinson, Shadow prices for measures of effectiveness, II: General model. *Operations Research* **41** (1993) 536 – 548
3. S. M. Robinson, Sensitivity analysis of variational inequalities by normal-map techniques. In: F. Giannessi and A. Maugeri, eds., *Variational Inequalities and Network Equilibrium Problems*, pp. 257 - 269. Plenum Press, New York and London, 1995
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10. M. C. Ferris and T. S. Munson, Preprocessing complementarity problems. In: *Complementarity: Algorithms, Applications and Extensions*, eds. M. C. Ferris, O. L. Mangasarian, and J.-S. Pang, pp. 143 – 164. Kluwer Academic Publishers, Dordrecht, 2001
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13. S. M. Robinson, False numerical convergence in some generalized Newton methods, 2001, accepted for publication in *Equilibrium Problems and Variational Models*, Eds. P. Daniele, F. Giannessi and A. Maugeri, Kluwer Academic Publishers, Dordrecht, 2003
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