STRATEGIC DEFENSE INITIATIVE ORGANIZATION
INNOVATIVE SCIENCE AND TECHNOLOGY OFFICE

Submitted - Summer 1986

DEVELOPMENT OF ORTHOGONAL FACTORIAL DESIGN APPROACH AS AN AID IN THE DESIGN OF RELIABLE MILITARY SYSTEMS

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INTRODUCTION

Recognizing the conditions that defense systems in space will have to endure, one cannot help but realize how important it is that such systems be reliable and available any time they are called upon to function. There is no time for corrections, if such corrections are even possible, action by a system has to be taken immediately and accurately, there is no room for malfunctions or errors. Putting aside, for a moment, the need for reliable operation of space military systems during a military operation, there is also a need to ensure that a malfunctioning 50-cent component, is not the cause of a major confrontation. Consider, for example, a simple resistor that fails and eventually leads to a false signal indicating an offensive move by the enemy. Such a signal could possibly result in a confrontation that is not called for. On the other hand consider a small component failure that renders the defense component inoperable and the weapon or other defense system returns to earth. It is very likely that such a return on enemy areas could be misinterpreted as a hostile action and again result in a major confrontation. Of course such problems involving the reliability and availability of systems are not uncommon on any military system or component. There is, however, a big difference in similar problems and their treatment between systems on earth and systems in space. The key points and differences could be summarized in-terms of space system peculiarities as follows:

- Space stationed systems cannot be checked as often and as thoroughly as their earth based counterparts.

- Such systems cannot undergo maintenance inspections and service normal periodical maintenance inspection and service.

- Space systems have to operate for prolonged periods of with original components.

- Even when it is recognized that a component or a system is malfunctioning, it cannot be repaired as - quickly and reliably as earth counterpart systems.

It might seem that reliability and availability problems can be taken care of very easily by simply designing and building a more reliable system. This in concept is very simple and very easy indeed. Redundancy of components and subsystems could very well take care of any reliability problems. Let us not overlook the fact, however, that such redundancy can lead to overwhelming cost increases and significant increases in weight and size.

This is where the Orthogonal Factorial Design techniques come to the rescue. These techniques were initially borrowed from the experimental field. They were later developed to address problems similar to those encountered in systems design, production and operational analysis.

In general, these techniques are based on the use of the orthogonal factorial matrix, a form of optimal regression analysis. Due to this orthogonality of especially prepared matrices, experiments or computer simulations of a given system or process, are performed at specific predetermined variable/component status combinations. Subsequent statistical evaluation of the responses, results in mutually independent regression coefficients to a functional prediction model. Even though analysis, using these techniques, cannot guarantee the identification of all possible problems, it is expected to be useful in determining and ranking importance of system components and functional component interactions that hidden in the design. This evaluation of component importance can be done with high confidence level and, furthermore, certain types of system/human interactions can also be investigated.

The Orthogonal Factorial Design approach was originally developed for the agricultural field in the early twenties by Fisher in England. Even though a-powerful method, because it used almost no conventional mathematics, it was not readily accepted by the scientific community. The method, however, is so powerful that it eventually made its way in manufacturing and a number of other fields in Japan and U.S.S.R. These techniques were not applied in the manufacturing field, in Japan, until after the second World War. They now have been developed to such extend, that no government contract is awarded, unless some factorial design technique is included as part of the proposed work. Furthermore, *approximately 90% of the private manufacturing* sector in Japan, is currently using the Factorial Design approach in research and quality control applications.. In the U.S.S.R., Orthogonal Factorial Design has been extensively used and perfected in areas ranging from the development of plastics to the manufacturing of automobiles, to strength of materials. Orthogonal Factorial Design techniques are taught to most graduate engineering students in the Universities, and is the required method in research and development sponsored by most government agencies, all military universities, specialty universities in applied chemistry, plastics, etc., are required to appoint research group leaders that have expertise in Factorial Design techniques.

Because of what are thought to be reliability problems, there is currently, an increased interest shown by many U.S. industries in using such techniques for system reliability and availability analysis. Unfortunately, the number of scientists and engineers adept in the techniques is very limited.. ,s a matter of fact, seminars have been organized by Japanese experts, to instruct major U.S. manufacturing industry personnel on using these techniques in the area **of** reliability and quality control.

Some of the advantages of the Orthogonal Factorial Design approach are summarized below:

- Provides accurate relationships between variables and experimental outcome (in this case relationships between component failure rate and system availability).
- Reduces the number of repetitions of the experiment required (in this case reduce the number of combinations of components or alternative system designs)..
- Results in cost effective processes, e.g.. in the case of agricultural applications, for which the methods were originally developed, increase land productivity while reducing fertilizer costs.

RELIABILITY PROBLEMS IN SPACE SYSTEMS

The very success of any strategic defense system, will depend on the successful operation of all the system components.. Failure rates **of** components are available both from the military and other non-related industries Such failure rate data, however, is based on components operations that do not at all resemble the hostile environments that would be encountered in space.. The data bases , therefore, are at best limited.. The uncertainty on the component failure rates could be detrimental to the very system they are used in. Furthermore if state of the art components are used, the data base for such components is for limited time operation, if it is at all existent. In the case that no reliability/availability data are available, new components would have to go through qualification for the specific intended use. , problem that is commonly encountered in trying to increase the reliability of a system, is that even though an identified weakness is corrected, the correction now results in problems in a different system ,area. More important than that, since the exact dependency of the system on a particular component is not explicitly known, a replacement or adjustment **of** a particular component, could very easily result in not only reducing rather than increasing reliability, but also rendering another part of the system completely inoperable.

Problems such as those identified above, are compounded when space systems are military systems. Long term unattended operations are a must and service of space military systems minimal, if available at all.. Reliable operation is crucial and assumed, and failure of a system at the wrong time, could have devastating results.

It is suggested that the Orthogonal Factorial Design is the answer to problems related to reliable operation of space based strategic military systems.

THE ORTHOGONAL FACTORIAL DESIGNG TECHNIOUES

The Orthogonal Factorial Design is based on the principles of combinatorial mathematics and relies heavily on simple statistical concepts.. Suppose we were interested in determining the effect of two components, X_1 and X_2, on a system output $A(X_1, X_2)$. Further suppose that the components could be in one of three states, S1=fully operational, S2=partially operational and S3=non-operational. We could device a series of experiments, varying the component states and measure the system output. The experimental design is shown in Table 1.

Table-1

	Component State		
Experiment #	**X_1**	**X_2**	**System Output**
1	3	3	A_1
2	2	1	A_2
3	2	3	A_3
4	3	1	A_4
5	1	2	A_5

Statistical analysis of the above results (least squares or some similar technique), would result in an empirical model for predicting the system output,

$$A(x_1, x_2) = c_0 + c_1x_1 + c_2x_2 + c_3x_1^2 + c_4^2$$

If we were to take the Factorial Design approach, and we wanted to get an accurate prediction model, then our experiment series would look like the one in Table 2.

Table-2

	Component State		
Experiment #	**X_1**	**X_2**	**System Output**
1	1	1	A_1
2	1	2	A_2
3	1	3	A_3
4	2	1	A_4
5	2	2	A_5
6	2	3	A_6
7	3	1	A_7
8	3	2	A_8
9	3	3	A_9

Evaluation of the results of the above experiment series, would result in the following prediction model:

$$A(x_1, x_2) = c_0 + c_1 x_1 + c_2 x_2 + c_{11} x_1^2 + c_{22} x_2^2 + c_{12} x_1 x_2 + c_{122} x_1 x_2^2 + c_{112} x_1^2 x_2$$

What is of great importance, is the fact that in the above equation (unlike the conventional least squares statistical techniques), each coefficient c, is a true measure of the importance of the corresponding term. For example, if in a real situation similar to the above, the following coefficients had been evaluated:

$$c_1 = 1.2$$
$$c_{22} = 1.29$$
$$c_2 = 2.5$$
$$c_{12} = 10.2$$

The conclusions that could be drawn would be as follows:

- First order effects of component X_1, and second order effects of component X_2, have approximately the same effect on system output.
- First order effects of component X_2, are twice as important as first order effects of components x_1.
- The effects of combining components X_1 and X_2, is five and ten times as important as the first order effects of components X_1 and X_1 respectively.

Conclusions such as these, would provide invaluable information as to possible modifications of the system, in order to optimize system output.

PROPOSAL

The Orthogonal Factorial Design in combination with other conventional reliability/availability analysis techniques, can provide a virtually perfect understanding and a flawless means of predicting a system's behavior under any conditions. The word "virtually", here is used as a substitute for "if time and money were infinite". One, of course, could by right argue that the same is true for a million other techniques, the problem is that neither time nor money available are infinite, and this is where lies the power of this approach. Given limits on both-time and money, application of the Orthogonal Factorial design will provide the most accurate information possible.. Judicious application of the technique will provide the following information about the system under study:

- Relative contribution of each component and each combination of components to the total system reliability..
- It will identify whether a component might be a problem due to the size of the data base for that component, or simply because the component is not of good quality.
- It will provide with component interaction information which will allow for the proper identification of the problem area, (e.g.. a given component by itself might be no problem, however, in combination with another component, it might not function correctly.
- Finally, it will result in a simple algebraic reliability prediction model, so that future similar system designs can be evaluated.. It is even possible that once such systems are space, the simple prediction model can be used to evaluate their reliability or availability if a component fails or its performance deteriorates due to the harsh environment.

SCOPE OF WORK

To develop an Orthogonal Factorial Design method to estimate reliability and to help in the design of defensive military systems, so that such systems can operate unattended and without maintenance for long periods of time.

To demonstrate application of Orthogonal Factorial Design to be used in the qualification of new state of the art components being developed for which no failure rate data bases exist.

To prepare an application manual for using the techniques of Orthogonal Factorial Design by SID personnel or SID contractors.

The proposed work is to be completed within one year, at which time, evaluation of the results by the SDI Organization would determine if further applications of the techniques could be of benefit and the effort could be expanded into a three year program.

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