USCEE REPORT #381

N 70 16705

NASA CR 107748

UNIVERSITY OF SOUTHERN CALIFORNIA

RESEARCH ON NEW TECHNIQUES FOR THE ANALYSIS OF MANUAL CONTROL SYSTEMS

PROGRESS REPORT NO. 8

George A. Bekey
Michael J. Merritt
Anil V. Phatak

December 15, 1968 - June 15, 1969

Prepared for the National Aeronautics and Space Administration under Grant Number NGR 05-018-022

CASE FILE COPY

ELECTRONIC SCIENCES LABORATORY

USC Engineering

RESEARCH ON NEW TECHNIQUES FOR THE ANALYSIS OF MANUAL CONTROL SYSTEMS

PROGRESS REPORT NO. 8

George A. Bekey
Michael J. Merritt
Anil V. Phatak

December 15, 1968 - June 15, 1969

Prepared for the National Aeronautics and Space Administration under Grant Number NGR 05-018-022.

I. INTRODUCTION

During the period December 15, 1968 to June 15, 1969, major efforts were directed towards (1) completing past research projects and subsequently presenting the findings in a published form, and (2) continuing research projects initiated during the previous year. Specifically, we are continuing work in decision processes of human controllers and on the human neuromuscular system.

Several papers were published in the areas of stochastic approximation, manual adaptive control and discrete human controller models. Work on the identification of human controller's strategy in discrete decision making is being continued and the results of preliminary experiments are presented herein.

In addition, a brief outline of proposed future research efforts is presented.

II. A GEOMETRIC APPROACH TO THE IDENTIFICATION OF DECISION ALGORITHMS USED BY HUMAN CONTROLLERS

M. J. Merritt and G. Meier

Human controllers decision making involves the selection of an appropriate response for a given control situation from among a finite set of allowable responses. The decision to initiate a discrete control action - pulsatile or continuous, the logic behind eye movement scanning rules or the detection of a covert event are but a few examples of decision making processes within the human controller. In the past, identification of the human controller's decision algorithms has relied on graphical or brute-force computer methods. The decision space (including all or some of the state variables) was multi-dimensional and modeled using general purpose multi-state decision elements (MSDE) having multiple inputs with adjustable weighting factors [1] and single decision outcomes as outputs. When the dimensionality of the decision space is three or higher, graphical techniques become cumbersome. The MSDE's, while computationally feasible are difficult to interpret physically because of the high dimensionality of the resultant decision surfaces. The goal of most human operator modeling is to gain insight into the physical processes involved.

The method described in the following uses MSDE's for modeling human decision making with constraints on the structure of the decision space, based on the practical system being studied. The approach is summarized as follows:

1. Select those variables from the state space which influence the decision process. The space comprising these variables is called the input space.

2. Define the output space as the union of a finite number of admissible output states (sometimes called decision outcomes).

3. Partition the input space. Then the input space is the union of single elemental spaces called hypercubelets.

4. The path in the input space traced out during a manual control task is called the input trajectory. As the input trajectory passes through a cubelet, the corresponding output state is recorded.

5. Associate each cubelet in the input space with one of the admissible output states. (This is done via actual input state trajectories.)

6. After all of the experimental data is processed, the input space is smoothed to fill in the output states of those cubelets not touched by the experimental input trajectories.

7. The smoothed input space is examined to locate all boundaries between the finite output states. All subsequent processing is performed on these multi-dimensional boundaries.

8. Each boundary is analyzed to find the best fit hyper-conic section. If a single conic section is not sufficient, then two or more conic sections may be used to fit the boundary in a piece-wise manner.

9. The complete model is comprised of the various hyper-conic section approximations to the experimental decision boundaries, and constitutes the resultant decison algorithm.

The primary advantage of this geometric approach is that the resultant decision algorithm of the human controller is obtained from a finite number of experimental input trajectories.

A. The Smoothing Algorithm:

The smoothing algorithm discussed in this section is applied to raw experimental data in the input space so as to yield output states for the "undefined" cubelets, that is, those cubelets in the input spaces that are left untouched by the raw data. The procedure is outlined as follows:

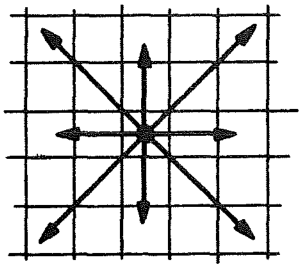
1. The density of output states in the neighborhood of every undefined cubelet is investigated.

2. The output state of an undefined cubelet is classified in a category whose density is highest in the neighborhood of the given cubelet. This denisty must exceed a certain threshold; otherwise the given cubelet is left undefined.

The threshold value chosen depends upon the location of the undefined cubelet with respect to the boundaries of the decision space for which the model is valid.

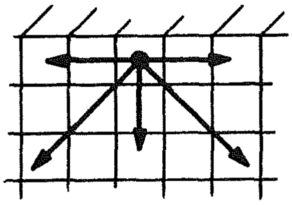
In a two dimensional input space three cases of interest are:

a. Interior cubelets - Here all the cubelets in the neighborhood of the undefined cubelet are defined. (see sketch below)



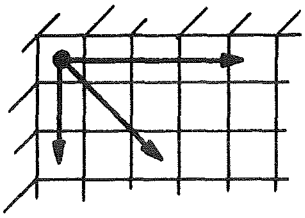
The output states of the neighborhood cubelets in eight different directions from the undefined cubelets are recorded. The output state of the cubelet is said to belong to that category whose density is the highest and greater than a threshold value of 0.75.

b. Edge cubelets - These are cubelets which lie on a boundary of the allowable decision space. (see sketch below)



The neighborhood of the undefined cubelet exists in only five directions. The cubelet's output state is assigned to that category whose density is highest and greater than a threshold value of 0.80.

c. Corner cubelets - These are cubelets at the intersection of two orthogonal boundaries of the allowable decision space. (see sketch below)



The neighborhood is investigated in three directions. The undefined cubelets output state is assigned to that category whose density is highest and greater than a threshold value of 0.67.

3. The distribution of the undefined cubelets changes with every smoothing operation. Hence several runs with the smoothing algorithm are generally necessary to define the input space. The process is terminated when the percent decrement in the undefined cubelets reaches some lower threshold value (picked by the programmer).

The application of the smoothing algorithm to the identification of decision regions in two simulated control tasks is discussed next.

B. Applications

Two manual control tasks simulated on a digital computer are shown in Figures 1 and 2 respectively. Data obtained are used to demonstrate the feasibility of the geometric approach to the identification of the decision surfaces used in the black box simulated human operators. The system input was a low frequency random appearing input (sum of sine waves with non-commensurate frequencies). Error, error-rate and controller output state (+1, 0, or -1) were recorded. After partitioning of the input space (i. e. error-rate versus error), the output state associated with each cubelet touched by the input (i. e. error) trajectory was determined as shown in Figures 3 and 4 (corresponding to Figure 1 and 2 respectively).

Since the plots in Figures 3 and 4 give only a rudimentary picture of the input space, the smoothing criterion (described above) is applied to characterize the output state for the undefined cubelets. The resultant smoothed input space is given by plots of Figures 5 and 6 respectively.

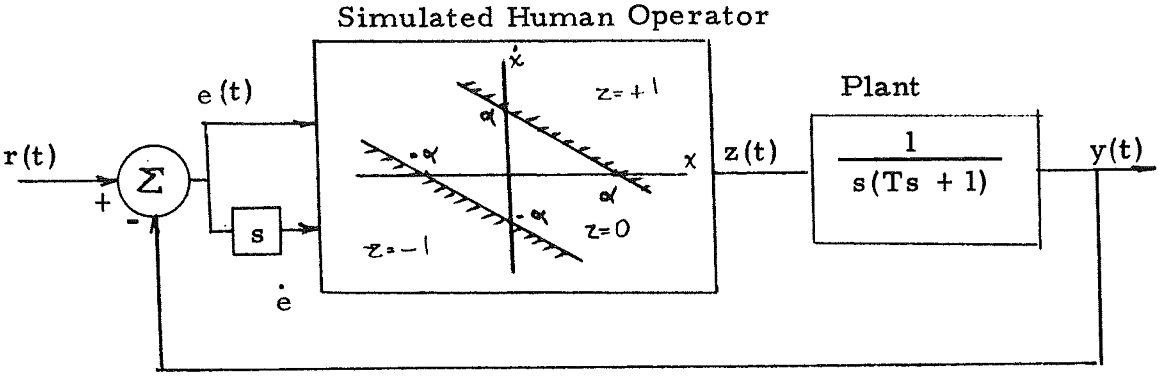


FIGURE 1

Simulated Manual Control Task 1

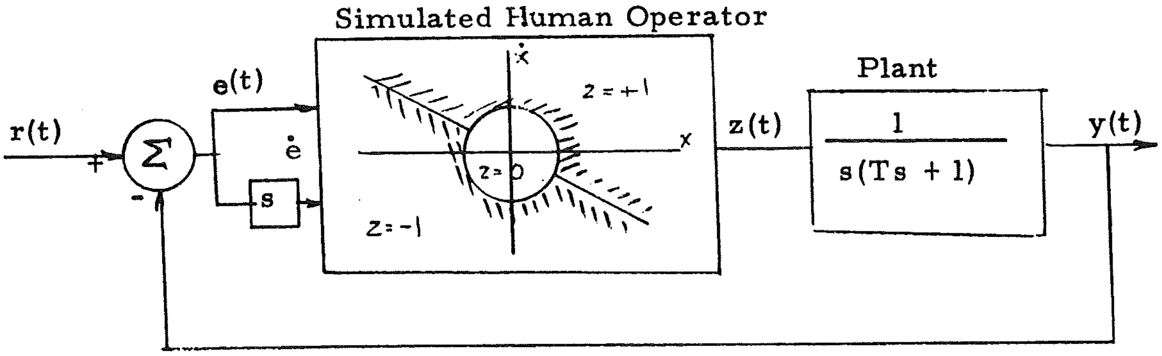


FIGURE 2

Simulated Manual Control Task 2

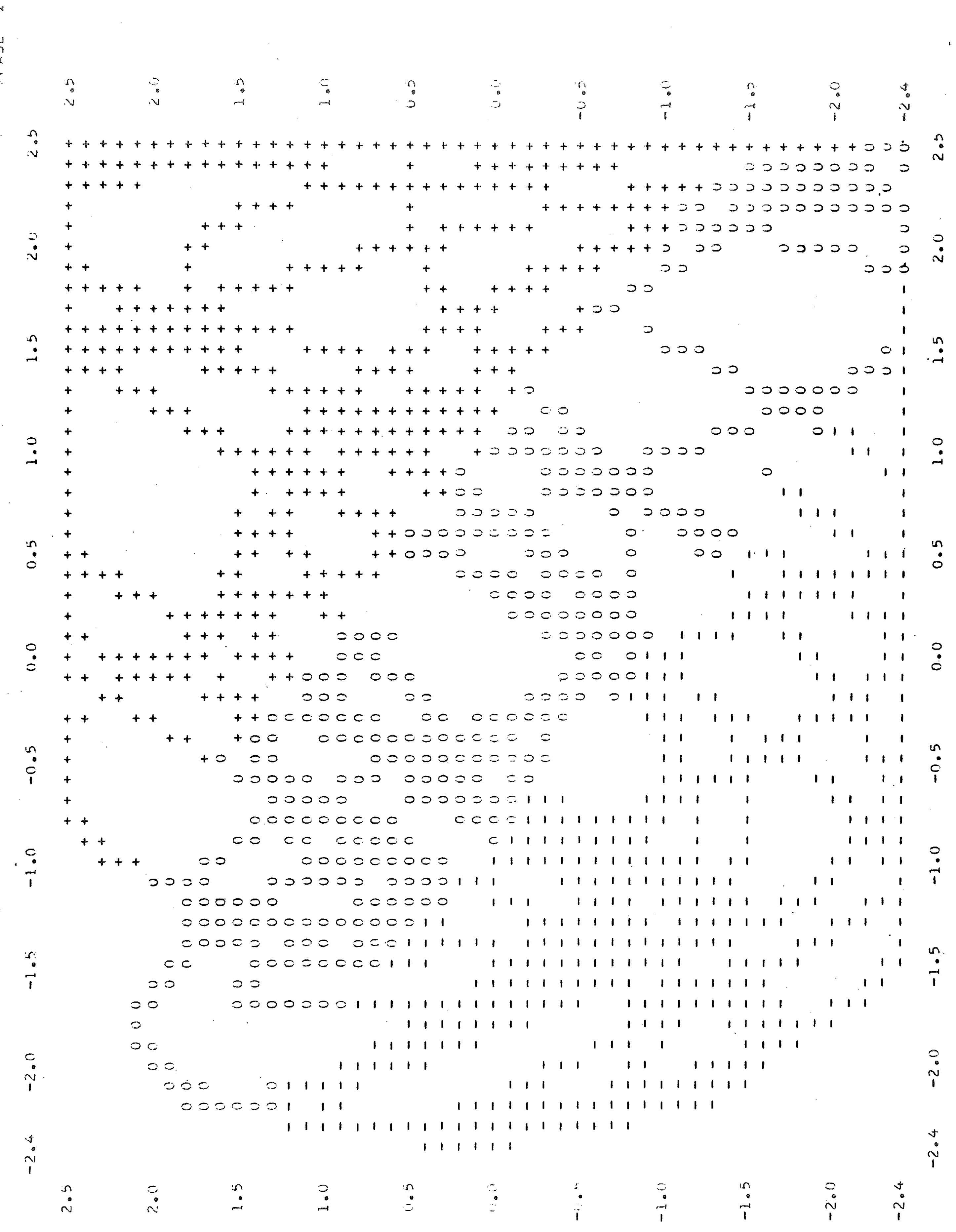
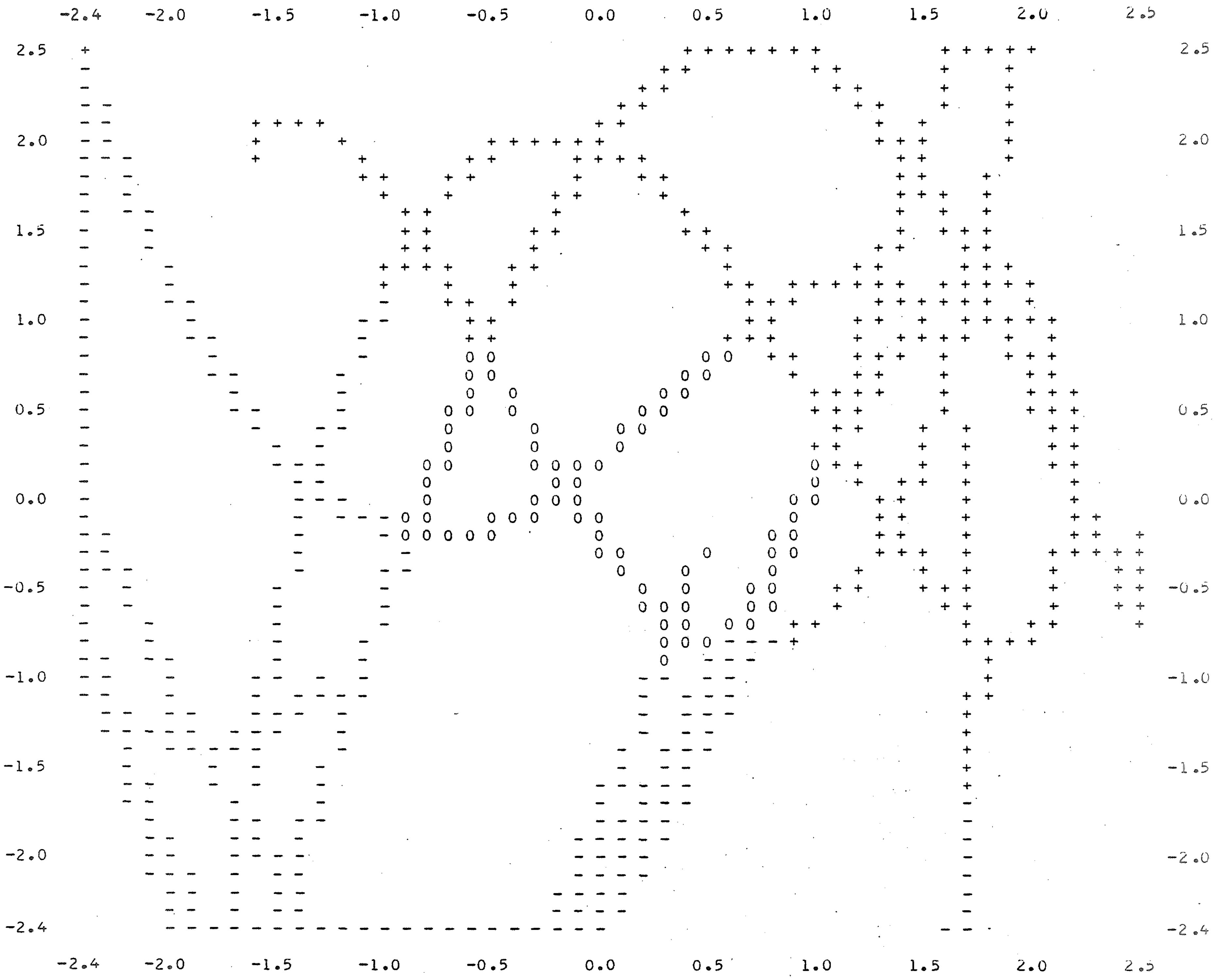


FIGURE 3 Task 1 Input Space - Raw Data

PHASE 1



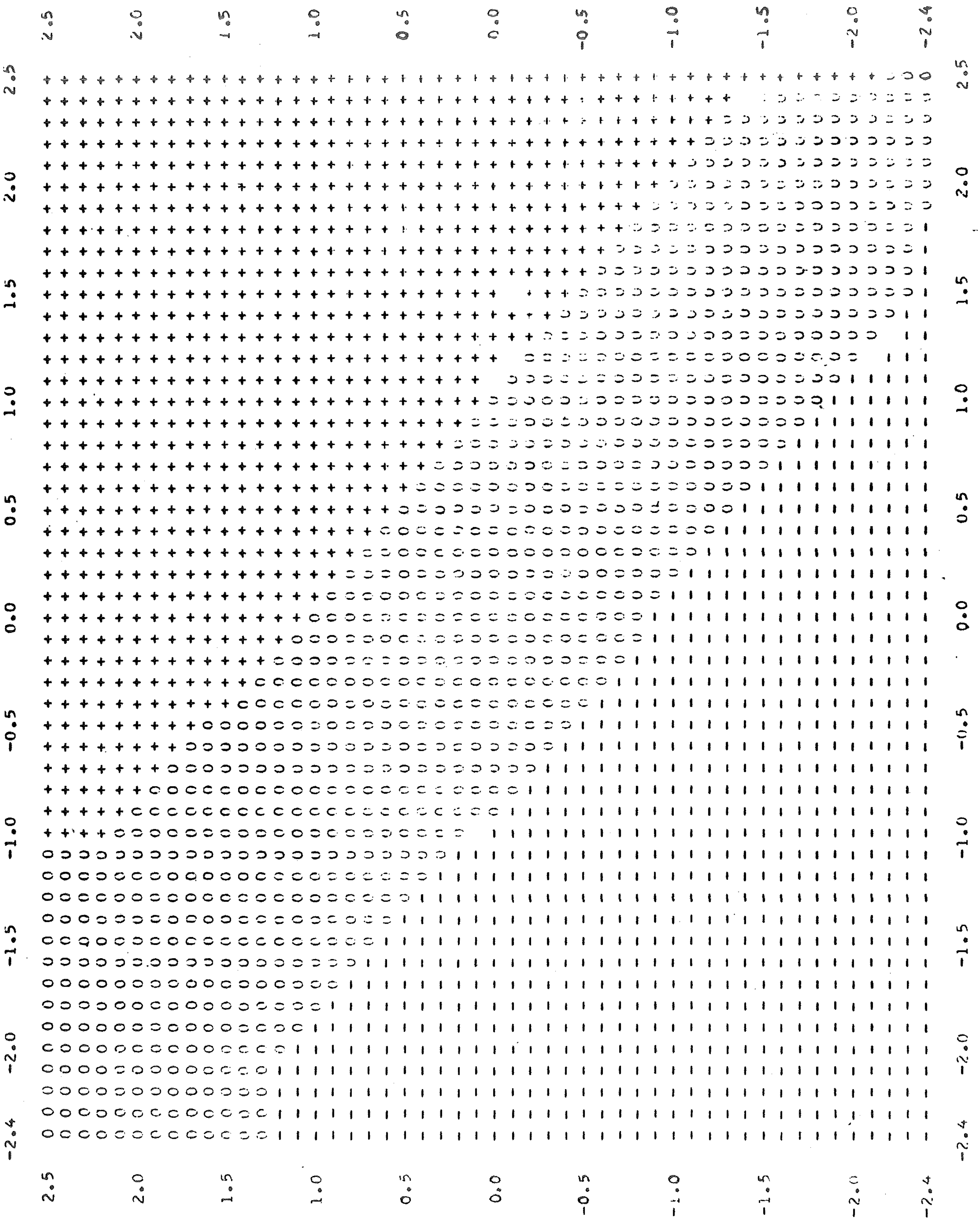


FIGURE 5 Task 1 Smoothed Input Space

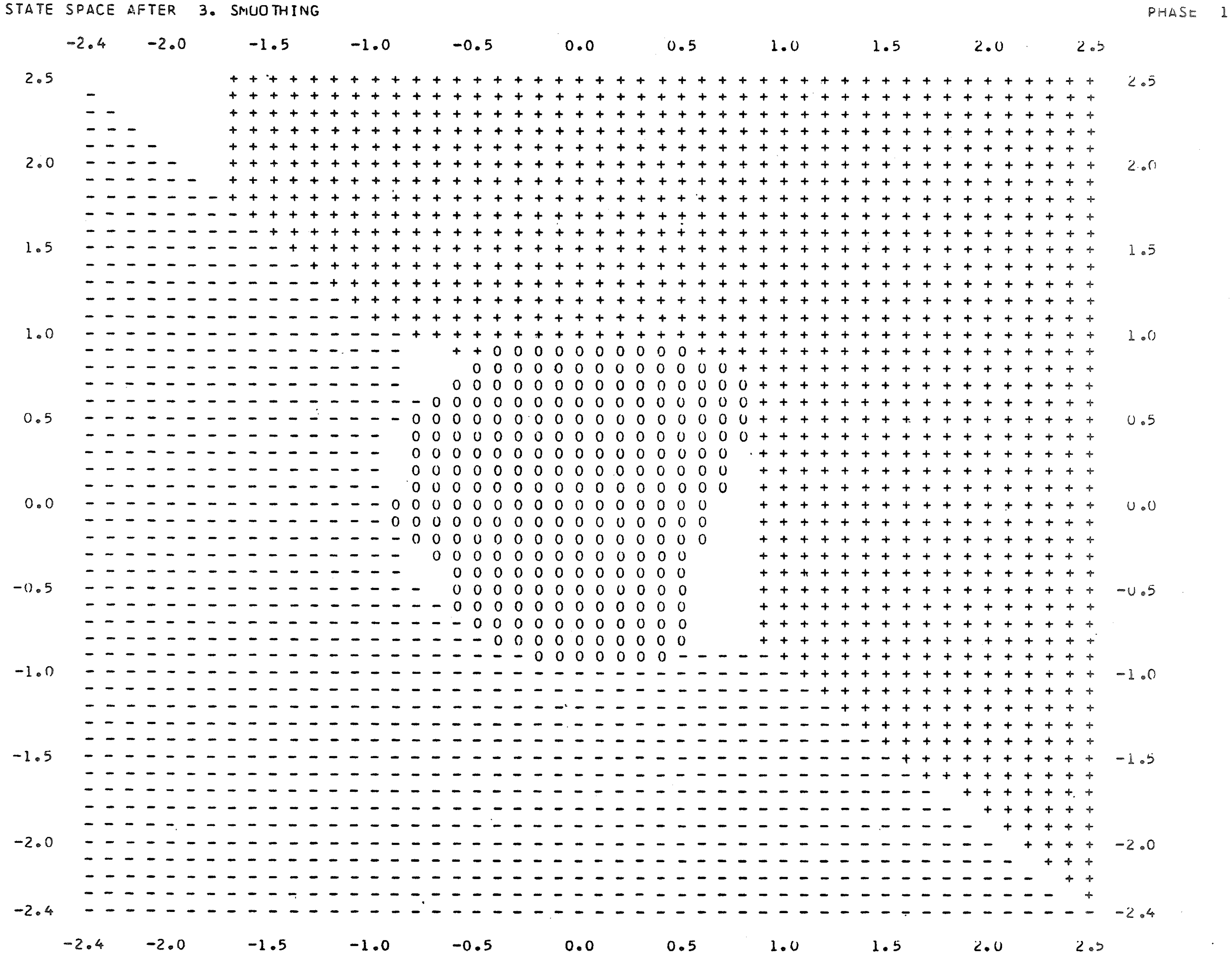


FIGURE 6 Task 2 Smoothed Input Space

The decision space is now defined (except for a few isolated cubelets) and the decision boundaries may be extracted as in Figures 7 and 8 respectively. Notice that they compare very favorably with the corresponding decision boundaries in Figures 1 and 2.

A conical section may be used to approximate the closed and open decision boundaries. Thus the coefficients in the general expression for a conic,

$$a(e^2) + b(\dot{e}^2) + c(e\,\dot{e}) + d(e) + f(\dot{e}) + g = 0$$

can be selected such that a least squares fit is obtained. The closed boundaries yield an ellipse for a fit while the open boundaries are best fit by either eccentric conic sections or straight lines $(a = b = c = 0)$. Decision boundaries in Figure 8 may be fit by an ellipse (circle) and straight lines, while those in Figure 7 are best approximated by two straight lines.

The two examples considered above illustrate the power of the proposed identification scheme. Extension to n dimensions is comparatively easy to achieve. Computationally this implies an increased memory requirement on the machine. The decision surface can still be represented by a section through a hypercone, which has a second order equation in n variables of the form:

$$\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}\, e_i\, e_j + \sum_{k=1}^{n} b_k\, e_k + c = o$$

$$\text{with } a_{ij} = a_{ji}$$

where e_i are the independent variables in the input space.

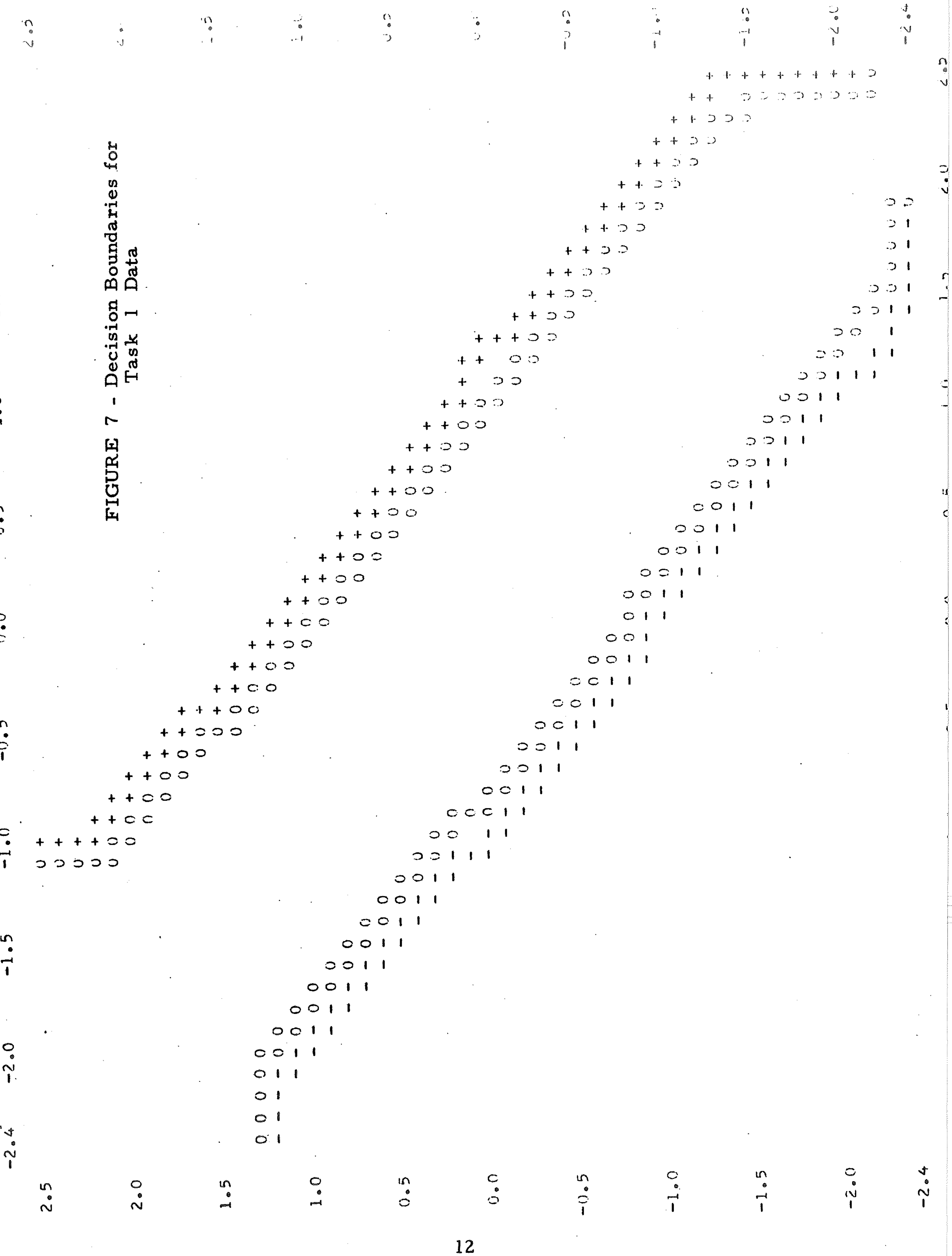


FIGURE 7 - Decision Boundaries for Task 1 Data

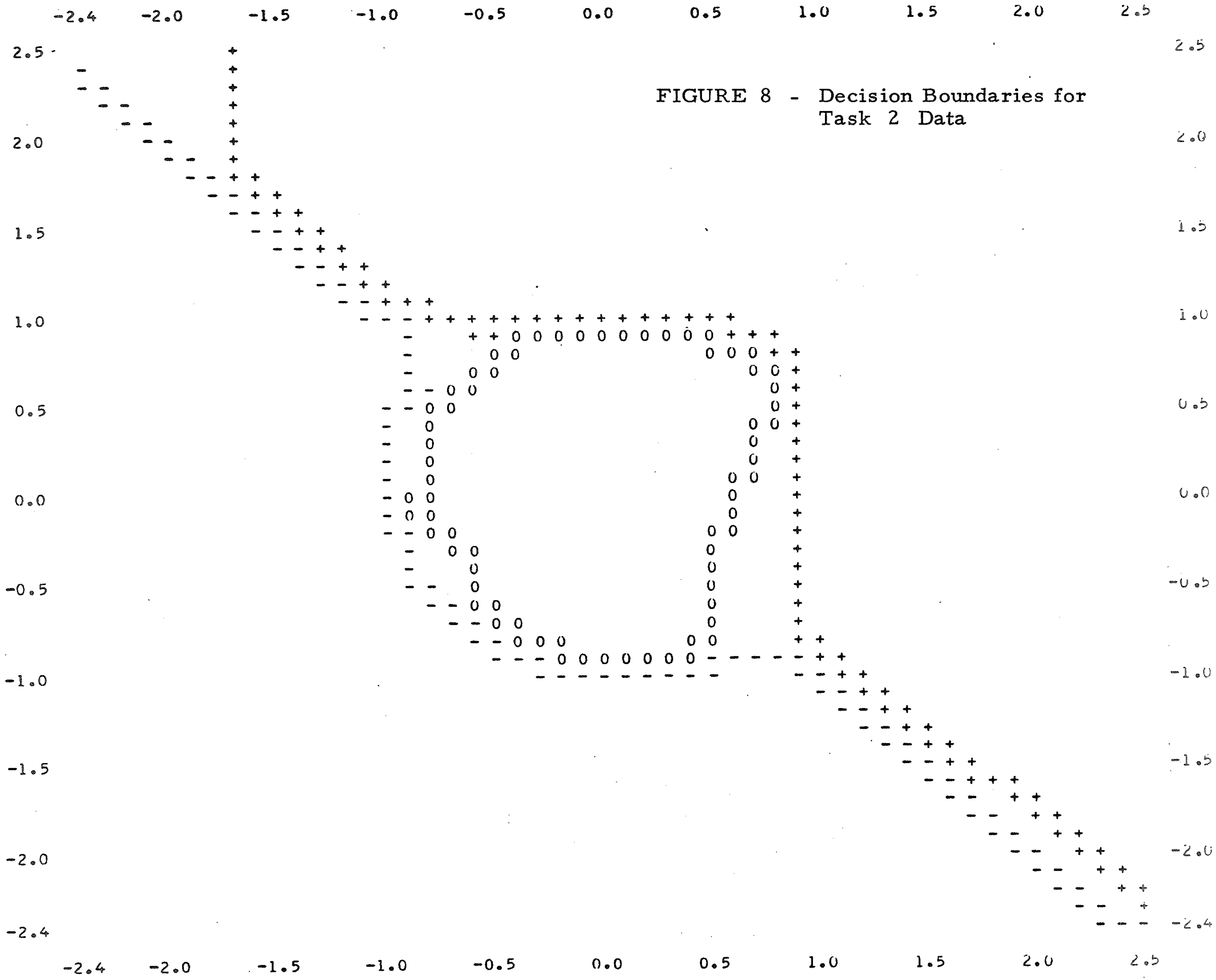


FIGURE 8 - Decision Boundaries for Task 2 Data

III. NEUROMUSCULAR SYSTEMS

L. Ostroy and G. A. Bekey

Mathematical models of muscle function in isometric tasks have been proposed by Coggshall [2]. In these models the aggregate myoelectric and force outputs $V_M(t)$ and $F_M(t)$ of a skeletal muscle are considered as random processes and their first and second order statistics described as functions of the statistics of the individual active motor units. Current research efforts are directed to validating the theoretical predictions by way of digital simulation of the proposed models. A synthetic electromyogram (EMG) can be computed if one knows the number of individual active motor units recruited for a given isometric muscle tension and the statistical distributions of their respective electrical activities. The purpose of such an approach is to get some insight into the inverse problem of identifying the number of motor units and their statistics from aggregate myoelectric activity of whole muscles. This method, if it proves feasible, can be used in the diagnosis of neuro-muscular disorders.

IV. PUBLICATIONS

Several papers were presented at various conferences and published in journals. These papers and their abstracts follow:

1. "Decision Processes in the Adaptive Behavior of Human Controllers", A. V. Phatak and G. A. Bekey, presented at the Fifth Annual NASA - University Conference on Manual Control, M. I. T., Cambridge, Mass., March 27-29, 1969; also accepted for publication in IEEE Transactions on Systems Science and Cybernetics, Vol. 5, No. 4, October 1969.

ABSTRACT

This paper is concerned with the development of a decision algorithm which simulates the rapid adaptive behavior of human controllers following sudden changes in plant dynamics. The control of a VTOL aircraft in hover following failure of the stability augmentation system is used as a specific example. The decision algorithm is based on the assumption that the human controller recognizes certain pattern features in the error-error rate phase plane. Experimental data, obtained from pilots facing four possible alternatives following the time of failure, are presented. The proposed decision algorithm is developed and digital simulation results are discussed. A theoretical justification for the algorithm, based on statistical decision theory, is presented in the Appendix.

2. "On Modeling the Adaptive Characteristics of Human Controllers", A. V. Phatak and G. A. Bekey, presented at the Conference on Applications of Continuous System Simulation Languages, San Francisco, June 30-July 1, 1969.

ABSTRACT

This paper presents the development of a decision-control algorithm which models the rapid adaptive response of human controllers following sudden catastrophic changes in plant dynamics. The specific control task chosen is that of manually controlling the roll axis of a simulated VTOL aircraft in hover following failures in the stability augmentation system. The decision algorithm is based on the assumption that the human controller is trained to recognize certain pattern features in the error-error rate trajectory. Actual human operator response data are used to identify the decision-control logic incorporated in the proposed algorithm. Finally, results from digital simulations of the proposed adaptive controller model in various failure situations are discussed.

3. "Identification of Human Operator Models by Stochastic Approximation", C. B. Neal and G. A. Bekey, presented at the Fifth Annual NASA - University Conference on Manual Control, M. I. T., Cambridge, Mass., March 27-29, 1969.

ABSTRACT

This paper discusses the application of stochastic approximation to the estimation of human operator model parameters. Both continuous and sampled-data models are considered. Stochastic approximation was used successfully for parameter estimates in both types of models. In the case of sampled data models, all parameters, including the sampling interval, have been estimated.

4. "Estimation of the Parameters of Sampled-Data Systems by Means of Stochastic Approximation", C. B. Neal and G. A. Bekey, presented at the Joint Automatic Control Conference, Boulder, Colo., 1969.

ABSTRACT

This paper discusses the application of stochastic approximation to the estimation of sampled-data system parameters, including the sampling interval. The sampled-data systems considered have a closed-loop configuration, continuous input and output signals, and error sampling. A continuous dynamic system follows a zero order hold. Sufficient conditions are given for the mean-square convergence of a stochastic approximation algorithm of the Kiefer-Wolfowitz type which is used to estimate all the parameters of the sampled data system. Simulation results are presented which illustrate the theoretical results. In addition, simulations indicate that good estimates of the mean value of parameters are still possible when the parameters have random components.

V. PROPOSED RESEARCH

We expect to begin several new projects during the coming year. Specifically, we intend to investigate the following areas.

1. Learning and Adaptive Systems

The adaptive characteristics of trained human controllers have been an object of study and investigation for the past eight years. However, only recently attempts have been made to obtain quantitative data and mathematical models describing the decision processes in the response of human controllers in certain non-stationary control tasks [3]. It is assumed in all these studies that the human operator has learned via training the appropriate adaptive control strategy for a given time-varying control situation. The adaptive model involves either pattern recognition concepts or model reference schemes. No attempts have been made to model the algorithm (i. e. the optimal pattern feature extraction or the best model reference scheme) used by the human in achieving a resultant steady-state adaptive controller structure. Thus, it wouldbe desirable to model the learning processes of the human controller in a specific control task. Knowledge gained from such a study would greatly benefit or augment control theoretic approaches to the design of self-organizing systems inaddition to its usefulness to manual control design.

2. Modeling the Neuromuscular System

The neuromuscular system comprises the effector part of the human controller (that part of the motor system beyond the spinal motorneurons). It is involved in the control and regulation of precise limb position and movement. Models based on physiology have been proposed for small perturbations of the limb position [4]. However, these are "literal" models since no numerical values for the various component parameters are used (if available).

The basic topology of the neuromuscular apparatus is fairly well documented. The main components are:

1. An Actuator - skeletal muscle and
2. Sensors, namely, (a) the muscle spindle which senses muscle length and length rate, (b) the Golgi tendon organ which acts like a muscle force transducer and (c) joint proprioception via the Ruffini endings.

It has been suggested that integration and weighting of various sensory pathways occurs at the spinal motor-neuron levels with gates and weighting provided by a separate element (perhaps the Renshaw Cells).

It is quite likely that the topology or the configuration of the system is a function of the specific control task. For example, there may be a distinct difference in the internal weighting of sensory information by the human controller while tracking transient inputs (steps, ramps, etc.) as against tracking low frequency random inputs. It may also be a function of the kind of manipulator used (force or pressure stick versus spring restrained stick).

It would be desirable to know the various hierarchical neuromuscular configurations possible and the methods by which they are recruited. However, before attempting such a task, it is mandatory that the individual physiological components be analyzed and modeled. Only with these subunit models available can one proceed with modeling the overall neuromuscular system. We hope to start with muscles and study their aggregate myoelectric activity as a function of the number of individual motor units recruited and their statistics. Actual human single motor unit data will by analyzed as a first step in the process of modeling muscle function. It is hoped that such an approach can be followed to its logical conclusions.

3. Discrete Human Operator Models

The algorithm described in Section II for the identification of decision surfaces may be applied to model human controller behavior in response to a non-stationarity in the input or in the plant dynamics. Thus step response data for various controlled element dynamics may be used for identifying the models of human controllers for transient inputs. Similarly, the adaptive response of the human operator to a step change in the plant dynamics can be analyzed to identify the discrete switching in controller strategy. Such a method, if feasible, can yield the various decision surfaces used in adaptive models of human controllers [3].

LIST OF FIGURE CAPTIONS

REFERENCES

1. Merritt, M. J. "Synthesis and Identification of Mathematical Models for the Discrete Control Behavior of Human Operators" (Ph. D. Dissertation), University of Southern California Electrical Engineering Report #202, May 1967.

2. Coggshall, John C. "Mathematical Models of Muscle" (Ph. D. Dissertation), University of Southern California Electrical Engineering Report #303, August 1968.

3. Phatak, A. V. "On the Adaptive Behavior of the Human Operator in Response to a Sudden Change in the Control Situation" (Ph. D. Dissertation), University of Southern California Electrical Engineering Report #277, May 1968.

4. McRuer, D. T., Magdaleno, R. E., and Moore, G. P. "Small Perturbation Dynamics of the Neuromuscular System in Tracking Tasks", NASA Report CR-1212, December 1968.