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25. Mapping an Operator's Perception of a Parameter Space*

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Operators monitored the output of two versions of the crossover model having a common random input. Their task was to make discrete, real-time adjustments of the parameters k and τ of one of the models to make its output time history converge to that of the other, fixed model. A plot was obtained of the direction of parameter change as a function of position in the (τ, k) parameter space relative to the nominal value. The plot has a great deal of structure and serves as one form of representation of the operator's perception of the parameter space.

INTRODUCTION

The major thrust of manual control research, including our own, has been concerned with closed loop, moment-to-moment control of dynamic systems by the human operator, the so-called inner loop control problem. This area is still important and work on it has led to many practical developments. However, as we learn to design more appropriate and sophisticated automatic control systems and to model plants more successfully, more emphasis should be shifted toward understanding man's higher level control processes, such as those involved in adjusting the parameters of an automatic flight control system or in deciding exactly when to override the automatic system to abort a landing.

There are many systems in which men participate directly in process control operations as system optimizers or parameter adjusters. However, there are also many jobs that involve great levels of responsibility for processes, but very little actual controlling. These jobs demand intimate knowledge of the system dynamics. The monitors need to keep abreast of the current status of system variables, but their information and expertise are rarely utilized. They are highly skilled, but it is difficult to specify in a job description exactly what they need to know, for their skills involve subtleties that are hard to express verbally.

One approach to the study of parameter controllers and systems monitors is to analyze their tasks in a decision theoretic structure as Sheridan (ref. 1) or Carbonell (ref. 2) have done: namely, to define the predictability of the information sources probabilistically, to define values and costs for taking samples of information, to derive a performance index, and to postulate what observers *should* do if they are to behave optimally. Although that is a useful and important approach, it has difficulty taking account of the operator's knowledge of system behavior. This probabilistic structure cannot easily capture his level of "understanding" of the system dynamics. The approach taken by Smallwood (ref. 3) and by Kelly (ref. 4) in which a state of internal knowledge is postulated comes closer to the conceptualization presented here.

In the development that follows we are attempting to derive ways of describing the operator's knowledge of the dynamics of a system as it should be used in a parameter control or monitoring situation. We will describe a paradigm, based on that of Nolan (ref. 5), that permits the experimeter to keep track of the operator's parameter adjustments as he converges on a match between a fixed and a variable set of dynamics under his control. By summarizing his

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adjustment behavior at each of several points in a two-dimensional parameter space, we have obtained a crude representation of his uncertainty in choosing which way to move in the space. We believe this representation may be useful for inferring how the operator perceives the space.

METHOD

Figure 1 shows the basic paradigm. Two systems are operated in parallel and are subjected to the same band-limited random input signal. One of the systems has its parameters set to fixed values that remain constant throughout an experimental trial. The other system has parameters that are under the control of the system operator. On a CRT the operator views the inputs to the two systems as two single dots aligned vertically and moving horizontally. The output for each system is represented as a pair of vertically aligned dots 3/4-in. apart and centered about an imaginary horizontal line passing through the corresponding input dot. Since the inputs to the two systems are identical, the operator may compare the relationship between each input and output, or he may pay attention primarily to the two outputs, which will be perfectly aligned in their horizontal motion when the variable system is adjusted to correspond to the fixed one. The subject's task is to adjust the parameters of the variable system from some initial setting until its behavior matches the behavior of the fixed system as closely as possible.

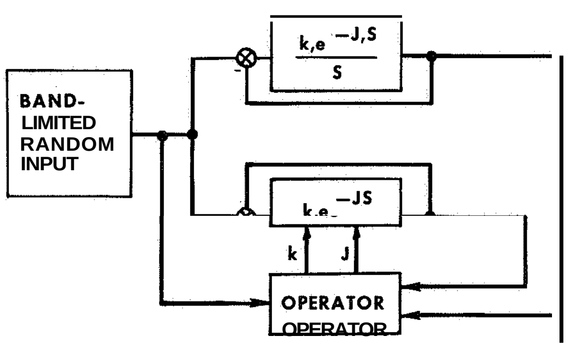
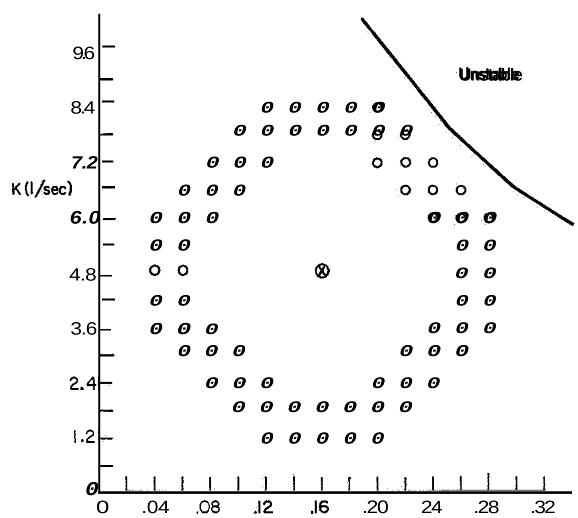


FIGURE 1.—Block diagram showing human operator as a parameter controller that attempts to match the variable parameters k and τ, to the values of the fixed system, k_1 and τ_1.



6 sec for the onset of a 700 **Hz** tone before they could proceed with the next adjustment. They were given **3** min in which to complete all adjustments on a given trial.

In order to give the subjects some initial intuition regarding the effects of the τ and k adjustments, they were told that the displayed inputs represented winding roads, and the displayed outputs represented the centers of two automobiles. The drivers were attempting to keep the centers of their automobiles aligned with the centers of the roads. However, their ability to do this was limited by two factors, τ and k. τ is the driver's reaction time, which is a pure time-delay that elapses before he can *start* to make a steering correction when the road takes a sudden turn. k is the relative "tightness" or "looseness" of the driver, and determines how quickly or slowly he will attempt to complete a steering correction once it has begun. The subjects' task, then, was to match the performance of the driver in the adjustable system to the performance of the driver in the fixed system. Subjects were also told that while these descriptions of τ and k were not meant to be misleading, they were only first order approximations to an accurate verbal description. They were therefore encouraged to characterize the effects of τ and k to themselves through their experience in making the adjustments. They were also encouraged by the original instructions and by trial-to-trial feedback to bring about correspondence with as few parameter changes as possible. The feedback concerned the minimum possible number of adjustments, how many they had made, and how many more, if any, would have been required to make a match.

Three college students who volunteered to serve in paid experiments and had no technical knowledge of control theory participated for 8 days each. They completed 18 trials per day for 4 days in order to complete the set of 72 initial conditions shown in figure 2. One trial for subject **A** was aborted because of an equipment failure. Each subject was tested in a different random order. On days 5 to 8 they completed a second replication of the 72 conditions in a new random order.

The direction that each subject chose to move at each point in the adjustment trajectory for each initial condition constitutes the major raw data of the experiment. In a few cases, especially for subject **A,** the adjustments were divergent to the point of exceeding the scaling limits of the parameters. In these cases the subjects were permitted to continue after being told that they had exceeded the limits.

RESULTS

One measure of the subjects' success at parameter control is the number of trials in which they failed to converge on the target values of k and τ within the allotted time. In the first block of days **1** to **4,** out of a total of 72 trials subjects **A,** B, and C failed to converge on **41,** 9, and 8 trials, respectively, within the given time limit. During block 2 on days 5 to 8, all subjects eventually converged on all trials.

The data were then analyzed in terms of the grid of possible states in τ-k parameter space in which the operator could find himself in relation to the target position at $k = \mathbf{4.8}, \tau = 0.16$. Depending on the starting point the optimal subject could reach the target position in 5, 6, 7, or 8 moves. Summing over all 72 initial position, the optimal subject would need 492 moves to complete all the trajectories optimally. As an indication of the success of the subjects, on days 5 to 8, the second replication, subjects **A,** B, and C took 922, 608, and 568 moves, respectively.

For each state in the space at which a trial was initiated or that was reached as a result of the operators' actions, a tally was made of the direction of movement away from that state. An example of such a tally is shown in figure **3.** The subjects could decide to increase or decrease τ by one unit or increase or decrease k by one unit. For each state the transition probabilities of movement in each direction were computed. This analysis treats the subjects' behavior at each state as independent of that at every other state, and therefore, as independent of how they got there. This independence assumption permits a rather simple graphical representation of these transition probabilities which is shown in figures 4, 5, and 6. The thin-lined vectors represent the actual transition probabilities on a scale such that the sum of the four possible probabilities equals a unit length of **1** cm. The bold vector

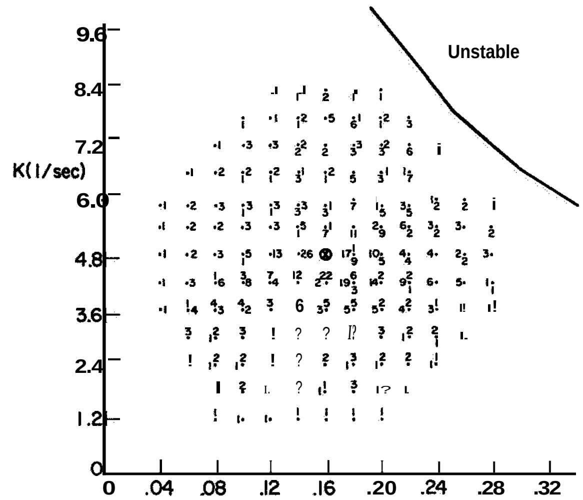


FIGURE 3.—Tally of subject B's movement through the parameter space.

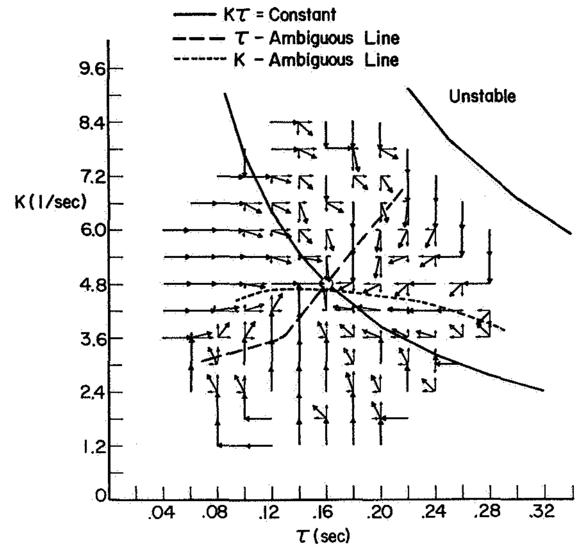


FIGURE 5.—Vector diagram illustrating subject B's average movement through the parameter space to reach the target dynamic condition.

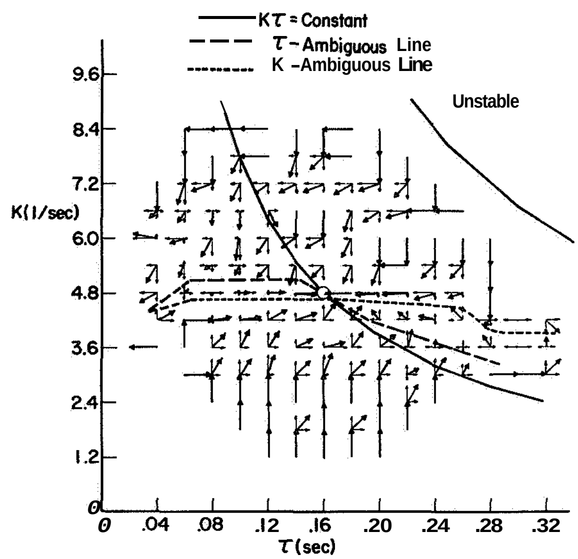


FIGURE 4.—Vector diagram illustrating subject A's average movement through the parameter space to reach the target dynamic condition.

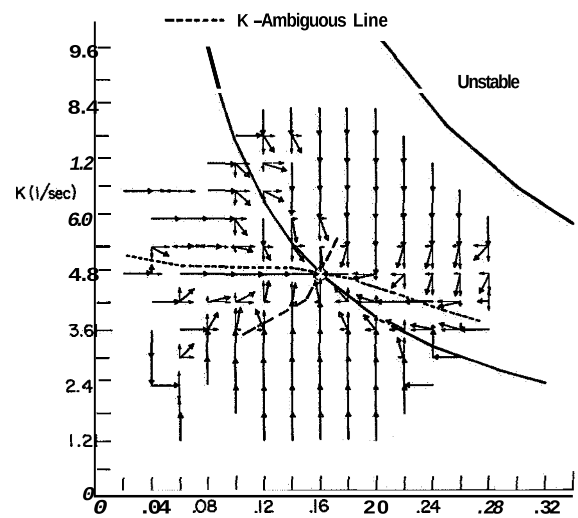


FIGURE 6.—Vector diagram illustrating subject C's average movement through the parameter space to reach the target dynamic condition.

represents the vector sum of the individual components of that state. In the plot for subject **A** any adjustments made after a parameter boundary was reached have been eliminated from consideration.

Since the states close to the target state are reached more frequently, (refer to fig. **3)** the vectors close in are more reliable than those near the **72** starting points. On the other hand, it is also intrinsic to this kind of analysis that the most data are available about state regions where the subjects are least certain what to do since, on the average, they spend more time making nonoptimal moves in these regions.

DISCUSSION

In general terms, the subjects displayed an impressive ability to decide which direction of change will bring them closer to the criterion condition. Subjects B and C are much more efficient than Subject **A,** but even he is able to converge on all the trials in the second block.

The vector representations of figures **4, 5,** and **6** are remarkably coherent and homogeneous. As one travels down a row or column of states, it is usually possible to observe a gradual change from movement predominant. in one direction to movement in another direction. Even in the case of subject **A,** who does not exhibit as much consistency as the others, it is frequently possible to map trends from state to state within the space. This coherence supports the idea that this record of the direction subjects choose to move from any particular state is indicative of their larger view of the space. They have not learned something that is specific to a particular state, but rather they have acquired a general model of the relation between points in the space and the target parameter values. It would be interesting to test how general this understanding is by measuring subjects' success when the target state is shifted to a new location. How much have they learned about the specific relationship and how much about model input-output behavior at states throughout the space.

Although there is homogeneity of the vector patterns, and, in general, the subjects tend to move efficiently toward the target state, the individual patterns of movement reflect a lack of orthogonality and symmetry in terms of the τ, k coordinates. On the basis of inspection a pair of lines have been drawn on the plots of Figures **4, 5,** and **6** to represent the point of transition from increasing to decreasing k adjustments and increasing to decreasing τ adjustments. In some regions, the path of these partitions of the space are ill-defined; in other areas they are quite well defined. The partitioning curves for subjects B and C are rather similar. For k adjustments, the line of ambiguity corresponds roughly to the $k=4.8\ \sec^{-1}$ line, implying that the interpretation of k in the subjects' mind corresponded closely with objectively-defined k. The same cannot be said for τ. Subjects B and C agree that the line of ambiguity lies roughly $45°$ clockwise from the objectively defined line at $\tau=0.16$ sec. Subject A's line for ambiguous τ closely resembles the line for ambiguous k, suggesting that perhaps subject **A** did not perceive two independent parameters. In any case, the ambiguous line for τ does not correspond with the $\tau=0.16$ sec axis. The conclusion from these observations is that the subjects introduce their own distortions and interpretations of τ adjustments, and that it seems likely that a more meaningful transformation of the space might be found.

The stability boundary is shown in figures 4, 5, and **6** and the solid line passing through the target state is a line of constant $k\tau$ product. It represents a level of stability corresponding to a phase margin of approximately **48".** In the case of subjects B and C it appears that the more efficient adjustment might be produced by replacing the τ adjustment control with a new adjustment parameter, x, that would permit simultaneous increases or decreases in k and τ by fixed amounts in the ratio of $0.6\ \sec^{-1}/0.02$ sec. Then, adjusting z would produce movement through the parameter space parallel to the line of ambiguity for τ revealed in this study. Of course, it could turn out that this new choice of adjustment parameters, k and z, is also distorted in a similar manner to k and τ.

OPEN QUESTIONS

This experiment has demonstrated the feasability of obtaining information directly from an observer that is useful for characterizing his general strategies for adjusting the parameters of a dynamic system. This method may also provide some insight concerning the properties of representation or model that these observers develop about the parameter space with which they are working. If such a map could suggest for some realistic systems the choice of parameters that is most directly and easily utilized by human observers, that would be a step forward.

Many questions remain. For example, do control system specialists or pilots deal with the space in the same way naive subjects do? How sensitive to the location of the target state is the generalized map of the space? Is the assumption of independence of states justified? What are the effects on convergence and map structure of introducing a fixed level of broadband noise in the output of the fixed model? Could subjects learn to match the dynamic properties of the two models if each were subjected to different, linearly uncorrelated, random input signals?

Whether or not this particular approach is ultimately judged productive, the problem of human monitoring and control of the parameters of relatively automatic systems remains an important one in need of further exploration.

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