D35

N79-15623

A METHOD OF MOTION SIMULATOR DESIGN BASED ON MODELING CHARACTERISTICS OF THE HUMAN OPERATOR

D. W. Repperger A. M. Junker

Aerospace Medical Research Laboratory
Wright-Patterson Air Force Base, Ohio 45433

Introduction

A problem of interest in the design of simulators is the development of a design criteria such that the simulators can be adjusted until they emulate real world situations. In this paper such a design criteria is obtained to compare two simulators and evaluate their equivalence or credibility. In the subsequent analysis the comparison of two simulators can be considered as the same problem as the comparison of a real world situation and a simulation's representation of this real world situation.

The design criteria developed here involves modeling of the human operator and defining simple parameters to describe his behavior in the simulator and in the real world situation. In the process of obtaining human operator parameters to define characteristics to evaluate simulators, measures are also obtained on these human operator characteristics which can be used to describe the human as an information processor and controller. Such modeling is motivated by the work of Fitts [1], Senders [2], Verplank [3], and others. First a study is conducted on the simulator design problem in such a manner that this modeling approach can be used to develop a criteria for the comparison of two simulators.

Symbols

ST(t)	Stick response of the human operator.
$\hat{x}(t)$	The Kalman filter's best estimate of ST(t).
$\nu(t)$	The residuals, innovations, or modeling error.
S	An approximation to signal power generated by the human.
N	An approximation to noise power generated by the human.

Symbols

$e(t)$, $E(s)$	The closed loop error signal and its Laplace transform.
ϕ	The discrete state transition matrix.
1σ	One standard deviation of a parameter estimate.
K_o	The Kalman Gain matrix.
A,B,H	The system gain matrices.
$x_1(t),x_2(t)$	State variables which describe ST(t) and $\frac{d}{dt}$ ST(t).
P,R,Q	Unknown covariance matrices.
$\hat{C}_k$	Sample covariance function (from the data).
$\hat{\rho}_k$	Sample, normalized autocorrelation function.
BW	An approximation to bandwidth of the human operator.

THE SIMULATOR DESIGN PROBLEM

In the comparison of two simulators or in the comparison of a simulator with a real world situation, an assumption is made as follows:

Assumption (1):
Simulator A = Simulator B if the human operator in Simulator A has the same "model characteristics" as the human operator in Simulator B.

The key term, "model characteristics" will be more explicitly defined via the modeling procedure. An alternative problem that can be solved via this procedure is the validation of a simulator in comparison to a real world situation. In this case the definition of simulator credibility is best described by assumption (2)

Assumption (2):
Simulator A = the real world if the human operator in Simulator A has the same "model characteristics" as the human operator in the real world situation.

In practice, the usefulness of assumption (2) has application if it is possible to take data in the real world situation as well as in the simulator. If the simulator can be adjusted so that the human operator parameters in the real world situation are close to the human operator parameters in the simulator, then the simulator has replicated the real world situation. This agrees intuitively with the definition of a replication of an experiment. A replication of an experiment is simply two empirical runs of data in which some variable shows consistency in both of the two empirical runs. In this case the variables that are to show consistency are the human operator model parameters. If these parameters show consistency between the real world situation and the simulator, then the simulator has replicated the real world situation. If the human operator appears the same in both the simulator and in the real world situation, and he rates the two to be the same subjectively, then the simulator has reproduced the desired environment from the point of view of the human.

The data base used to study the measures of simulator credibility involves a washout experiment as discussed in [4]. This experiment provides a unique opportunity to study how well the simulator replicates the real world situation.

THE G-VECTOR TILT WASHOUT EXPERIMENT

The G-Vector tilt washout experiment conducted at the Aerospace Medical Research Laboratory provides a data base to investigate the simulator credibility question. The data base used here involved a large centrifuge which has the capability of positioning the roll axis normal to the earth's gravity (called 0°) or parallel with the earth's gravity vector in which the subject is on his back or supine (called 90°). Six experimental conditions were considered in this study.

0° Conditions (Upright Position)	90° Condition (Subject on his back)
0° Motion	90° Motion
0° Washout - Attenuation only	
0° Washout - 1st. order washout	
0° Washout - 1st. order + attenuation	
0° Washout - 2nd. order	

As the subject makes a command stick response, the simulator rolls to simulate an aircraft in a banking maneuver. It is obvious that in the 0° (upright) motion case the human has both tilt cue information as well as angular acceleration cue information. In the 90° (subject on his back) motion case, the human does not have the tilt cue information. The four washout conditions were conducted at 0° (upright position) and a washout circuit was installed between the stick response and the plant's roll characteristics (Fig. (1a-b)). The effect of the washout circuit is to distort the motion cues to the human.

The manner in which this data base is equivalent to the simulator credibility problem is that the "real world" is defined as the 90° motion case.

The question is then asked, which washout scheme at 0° is closest to the real world 90° motion case? The 0° washout conditions contain reduced tilt cue information and also contain some distorted motion cues from the washout circuits. The modeling procedure which enables the determination of an equivalence definition between two simulators is presented next.

THE MODELING APPROACH

Figure (2) illustrates how the modeling approach was conducted here. After the data was collected from the various experimental conditions a post experimental analysis was conducted with a model developed in such a manner that the human operator can be modeled as an information processor and controller. With reference to figure (2), the input to the model is the time series e(t) (the displayed error signal). The purpose of this modeling approach is to choose model parameters such that the model's output $\hat{S}(t)$ is an accurate representation of the measured stick response of the human. The measure of modeling accuracy is expressed in the residuals or output modeling error $\nu(t)$ which satisfies:

$$\nu(t) = ST(t) - \hat{S}(t) \tag{1}$$

If the model is appropriately fitted to the data, then $\nu(t)$ should be a random white process which satisfies:

$$\text{mean} \, [\, \nu(t) \,] = E[\nu(t)] = 0 \tag{2}$$

$$\text{var} \, [\nu(t)] = E[\nu(t)\nu^{T}(\tau)] = R \, \delta(t-\tau) \tag{3}$$

It will be necessary in the subsequent analysis to test $\nu(t)$ for whiteness and determine R of equation (3). If $\nu(t)$ is a random white process, then the expected value of the model is equal to the expected value of the human's output. This is one method to validate such a model. A simple model structure is discussed next to describe the human's characteristics of interest.

A SIMPLE MODEL TO DESCRIBE HUMAN OPERATOR CHARACTERISTICS

It is desired to develop a model to characterize the human operator parameters of interest for this study. From previous studies [5,6], other simple representations of the human which have application in specific situations have been developed. In this paper a modeling approach will be used that will give rise to simple methods to characterize human operator parameters across several experimental conditions (or simulator designs). These modeling characteristics turn out to be analogous to an information theory representation of the human. Using the definition of channel capacity:

$$\text{channel capacity} = \text{Bandwidth} * \log_{10} \left(\frac{S+N}{N} \right) \tag{4}$$

The Bandwidth term is analogous to speed and the term $\log_{10}(\frac{S+N}{N})$ is analogous to accuracy. If the human operator has characteristics similar to an information channel, one would expect a product of the form of equation (4) to be invariant over several experimental conditions. It is then necessary to determine only two characteristics of the human operator in this representation of responses. To determine bandwidth, use is made of the human describing function plots. In the determination of the accuracy measure, a Kalman filter must be used.

From figure (3), it is desired to have a method by which an approximate measure of human operator signal/noise ratio can be determined. In this modeling procedure, the Kalman filter is initially specified to have input-output characteristics similar to those obtained from the describing function with the addition of some phase lag to account for the time delay of the human. The unknown Kalman gain coefficients (which represent the uncertainty terms or covariance matrices) are updated [7] in such a manner that the residuals $\nu(t)$ are white. The signal to noise ratio can then be approximated by:

$$\frac{S+N}{N} \approx \frac{\sum_{i=1}^{N} [ST(t_i)]^2}{\sum_{i=1}^{N} [\nu(t_i)]^2} \qquad (5)$$

It is noted that the variance of the residuals $\nu(t)$ are a measure of human uncertainty with respect to the error signal. This is true because the Kalman filter output $\hat{x}(t)$ is that portion of the stick response correlated with the error signal. The residuals $\nu(t)$ are that portion of the stick output not correlated with the error signal. This definition of human uncertainty differs from the classical definition of remnant [8,9] which is defined as that portion of human response not correlated with the input forcing function. This definition of human uncertainty is concerned with that part of the human response which is totally non-productive in reducing the error signal. This is easily seen to be true by noting that $\nu(t)$ when passed through the plant and around the loop still is uncorrelated with the error signal. Hence it cannot constructively be used to reduce the error signal because of its orthogonality to it. This measure of human uncertainty is a true measure of human output not useful in the tracking task. Next, a description of the measures of bandwidth and accuracy obtained from this modeling procedure are presented.

CALCULATION OF BANDWIDTH

In the computation of a measure of the bandwidth of the human operator, several difficulities exist in attempting to treat the human as an information channel [10]. This is due to difficulities in determining the true describing function from measured data variables and the effects of correlation between the human's remnant response and portions of the measured error signal. In this paper several approximations will be made. Figure (4) illustrates the describing function of the human for the 0^{o} motion case. Across the six experimental conditions considered here, the shape of the human operator describing function remained essentially the same; the major change between experimental conditions was only due to the d.c. gain values where the describing function was at a maximum. The ensuing analysis was conducted on the spectrum generated by the target frequencies. The reason it is necessary to work with the target frequencies is that if the target forcing function were zero, the describing function of the human operator obtained from only the human operator response (or for small values of disturbance input) is just equal to -1/plant. This result is well known [10,11].

From the target spectrums all experimental conditions are rated in order of their maximum gain value (table I). From table I it is seen that 0° static has the lowest gain value. The largest frequency the human will pass for this value of gain is now determined for each experimental condition.

This definition of the human operator bandwidth is the highest frequency at which the human will respond with gain of 0.5 db. In other words across all experimental conditions, the range of frequencies (from 0.0 radians and upward) is obtained that the human will pass with gain greater than 0.5db. In this manner a normalization is conducted on one experimental condition versus the remaining experimental conditions. This is a logical definition of human bandwidth and is one of many possible methods to approximate the bandwidth of a control system [12]. Measures of human uncertainty in tracking are determined next.

Table I - Bandwidth Computation - Subject - Eric

Experimental Condition	Maximum Gain in db	Bandwidth $\triangleq$ Higest Frequency where gain $\geq$ 0.5 db	1σ
0° Motion	6.5db	10.8 Rad/Sec	2.0
Washout Attenuation only	4.8db	9.8 Rad/Sec	0.3
90° Motion	4.5db	9.5 Rad/Sec	0.7
Washout 1st Order + Attenuation	3.5db	9.2 Rad/Sec	1.1
Washout 1st Order	2.9db	8.3 Rad/Sec	0.8
Washout 2nd Order	3.3db	8.2 Rad/Sec	1.1
0° Static	0.5db	7.3 Rad/Sec	1.0

MEASUREMENT OF ACCURACY OR SUBJECT UNCERTAINTY

With reference to figure (5) it is desired to update the model parameters in such a way that the innovations sequence $\nu(t)$ is a white, random process. The method of updating the parameters is based on an algorithm [7] which is actually a maximum liklihood procedure. In this manner a unique value of the optimal gain can be determined which maximizes the probability density function of the structure of the assumed model based on all the available data points. The optimal gain is the principal part of the discrete Kalman filter model which is described by:

$$\hat{x}_{i+1/i} = \phi \hat{x}_{i/i} + \int_0^{\Delta t} e^{A\tau} d\tau B \, col[e(t), \dot{e}(t)] \quad (6)$$

$$\hat{x}_{i/i} = \hat{x}_{i/i-1} + K_o [z_i - H \hat{x}_{i/i-1}] \quad (7)$$

where $\hat{x}_{i/i}$ is the minimum variance estimate of the human's stick response. The matrix ϕ is the discrete transicion matrix associated with the human's transfer function determined as follows:

$$\text{Let} \qquad \frac{ST[s]}{E[s]} = \frac{d(s+a)}{(s+b)(s+c)} \quad (8)$$

i.e. a fit of one zero and two poles is conducted on the human's transfer function to the describing function data (Bode plot). The coefficients a,b,c, and d are adjusted to try to match the phase data as well as the magnitude data. Implicitly the human's time delay has been included in the representation (8) through the adjustment of the parameters b and c. Future work will be done to study more exact fits. The matrix ϕ is then determined via $\phi = e^{A\Delta t}$ where Δt=.04 seconds (the sampling rate) and the matrix A is determined via:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = A \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + B \begin{bmatrix} e(t) \\ \dot{e}(t) \end{bmatrix} \quad (9)$$

where

$$x_1(t) = ST(t)$$

$$x_2(t) = \frac{d}{dt} ST(t)$$

and equation (9) is the time domain representation of equation (8). The matrix H in equation (7) is specified by $H = [1,0]$. The Kalman gain K_o satisfies:

$$K_o = P H^T (HPH^T + R)^{-1}$$

$$P = \phi [P-PH^T(HPH^T + R)^{-1} HP]\phi^T + Q$$

where the covariance matrices Q and R describe the human's uncertainty in the tracking task. The manner of obtaining the Q and R matrices is based on the algorithm in [7]. Initial matrix values denoted as Q_o and P_o are chosen. In order to establish the updating rule, it is necessary to define the sample covariance function.

Let:

$$\hat{C}_k = \frac{1}{N} \sum_{i=k}^{N} \nu_i \nu_{i-k}^T$$

is a sample covariance function. The matrices R and Q are now updated [7] via:

$$R_k = \hat{C}_o - H(P_k H^T)$$

where

$$P_k H^T = K_o \hat{C}_o + A^* \begin{bmatrix} \hat{C}_1 \\ \hat{C}_2 \end{bmatrix}$$

where

$$A^* = (\overline{A}^T \overline{A})^{-1} \overline{A}^T$$

and

$$\overline{A} = \begin{bmatrix} H\phi \\ H\phi(I-K_o H)\phi \end{bmatrix}$$

and finally Q is determined via:

$$Q_k = P - \phi K R_k K^T \phi^T - \phi(I-KH)P(I-KH)^T \phi^T$$

This algorithm has been shown to converge [7] and is equivalent to maximizing the log-likelihood function of the model structure conditioned on the data.

The final validation of this modeling effort is the need to test the residuals for whiteness. To accomplish this goal the normalized auto correlation function $\hat{\rho}_k$ is computed as follows:

$$\hat{\rho}_k = \frac{\hat{C}_k}{\hat{C}_o}$$

The test of whiteness of the residuals is a 95% whiteness test on $\hat{\rho}_k$. The 95% confidence limits for $\hat{\rho}_k$ are $1.96/\sqrt{N}$ where N is the number of samples. The band $\pm 1.96/\sqrt{N}$ is constructed about zero. If less than 5% of the sample points lie outside the band, the sequence is white. If more than 5% of the sample points lie outside the band, then a significant correlation exists in the residuals and the sequence is not white. Figure (6) illustrates the sample auto-correlation function obtained here from the data after the residuals have been whitened via this algorithm.

RESULTS FROM THIS ANALYSIS

Figure (7) represents the type of diagram obtainable from this type of analysis procedure. The vertical axis is a plot of the measure of bandwidth as shown in Table I. The horizontal axis indicates numerical values of the accuracy measure or S/N ratio obtained here. Also plotted is the curve of constant capacity based on this analysis procedure. The numerical values resulting from this investigation of the data are given in Table II:

Table II - Speed - Accuracy Results

Exp Condition	Mean BW	1σ of BW	N=Mean $\log_{10}S/N$	1σ $\log_{10}S/N$	Mean Capacity $BW*\log_{10}(1+S/N)$
0° motion	10.8	2.0	3.265	.191	34.346
Washout Attenuation only	9.8	0.3	3.278	.088	31.719
90° motion	9.5	0.7	3.358	.089	31.5025
Washout 1st order + Attenuation	9.2	1.1	3.378	.064	30.79
Washout 1st Order	8.3	0.8	3.373	.043	27.813
Washout 2nd Order	8.2	1.1	3.412	.082	27.634

Also plotted in figure (7) is the invariant rule:

$$BW * \log_{10}(1+S/N) = \text{Constant} = 30.6 \tag{11}$$

The constant 30.6 is the mean of the values of capacities obtained in the right most column in Table II. From figure (7) it is noted that most of the experimental conditions fall near this line.

Figure (7), by itself, is the diagram which can be used to assess the fidelity of a simulator in comparison to the real world data. If 90° motion is considered the real world situation, the washout scheme closest (distance wise) to this situation is 1st. order + attenuation. The other washout schemes are sucessively further away in this diagram and therefore, further from reality. The reason why it is said that the two experimental conditions best replicate each other is that the human exhibits almost the same bandwidth (or speed characteristics in tracking) and almost the same uncertainty characteristics (as measured by the S/N ratio).

Another interpretation of figure (7) is to consider the inverse problem associated with modeling; i.e. given the model parameters, can an analog simulation be built which will recreate the original empirical data. If the human in the loop were replaced by a quantitative description (e.g.

bandwidth and S/N ratio), the analog simulations of the 90^o motion case and washout 1st order + attenuation would most closely replicate one another. This is true because the only difference between the two simulations would be the parameters which describe the human operator. If these parameters are close to one another in some sense, then these simulations would best match. This is the motivation for using figure (7) to study simulator fidelity.

One additional comment needs to be made about why the washout scheme of 1st. order + attenuation best matched the 90^o motion case. The 0^o washout condition provided tilt cue information but the 1st. order + attenuation washout filter phase lag had the effect of distorting these tilt cues sufficiently to replicate the 90^o motion case. For the case of attenuation only, the tilt cue had an effect closer to 0^o motion (as expected). Also, as the washout scheme added more phase lag (2nd order case), the deviation from reality became more pronounced and the human operator dropped his bandwidth accordingly.

Future Research

The primary approximation used here was in the evaluation of human operator bandwidth. This approximation also effected the S/N ratio because the A matrix in the Kalman filter depends on this approximation. Future research will consider more accurate methods of evaluating bandwidth and including human time delay. In addition, a comparison will be made in the information rate obtained here to results from discrete tasks (approximately 3.0 bits/sec [13]) and to other information measures obtained from vision [14], reading [15], and control systems in general [16]. Another approximation utilized here was that the S/N ratio of the human was assumed to be constant over the entire frequency spectrum. In [3] the analysis procedure was able to study the capacity measure across the entire frequency spectrum. The procedure considered here can be extended in this respect. Also, since the analysis conducted here only involved one subject, future work will consider this analysis across different subjects, and use will be made of these measures of human invariance and subjective uncertainty in various task situations.

SUMMARY AND CONCLUSIONS

A study of design rules for the evaluation of a simulator's fidelity to the real world situation was conducted. The measures of model parameters obtained here give rise to information-theoretic models of the human operator. It appears that an invariant rule may exist on the human's ability to do information processing over a variety of different experimental conditions.

REFERENCES

1. Fitts, P.M.,"The Information Capacity of The Human Motor System in Controlling the Amplitude of Movement", Journal of Experimental Psychology, 1954, 47, pp. 381-391.

2. Senders, J.W. and J.J.M. Posner,"A Queueing Model of Monitoring and Supervisory Behavior", in Monitoring Behavior and Supervisory Control, by T.B. Sheridan and G. Johannsen, Plenum Press, 1976.

3. Verplank, W.L.,"The Facilitating Effects of Uncertainty in Long-Term Manual Control", Proceedings of the 1977 International Conference on Cybernetics and Society, September, 1977, Washington, D.C.

4. Jex, H.R. and A.M. Junker, "Roll Tracking Effects of G-Vector Tilt and Various Types of Motion Washout", The Fourteenth Annual NASA - University Conference on Manual Control, April 25-27, 1978, Los Angeles, California.

5. Repperger, D.W. and A.M. Junker, "Using Model Order Tests to Determine Sensory Inputs in a Motion Study", The Thirteenth Annual Conference on Manual Control, MIT, Cambridge, MA., 1977

6. Repperger, D.W. and A.M. Junker, "Performance Evaluation of Tracking Based on a Low Pass Filter Model", Eleventh Annual Conference on Manual Control, NASA TM X-62,464, pp. 599-624.

7. Mehra, R.K.,"On The Identification of Variances and Adaptive Kalman Filtering", IEEE Transactions on Automatic Control, Vol. AC-15, No. 2, April, 1970, pp. 175-184.

8. Jex, H.R.,R.W. Allen, and R.E. Magdaleno, "Display Format Effects on Precision Tracking Performance, Describing Functions, and Remnant", AMRL-TR-71-63, August, 1971.

9. Levison, W.H., S. Baron, and D.L. Kleinman,"A Model for Human Controller Remnant", IEEE Transactions on Man-Machine Systems, Vol. MMS-10, No. 4, pp. 101-108, December, 1969.

10. Wingrove, R.C., "Comparison of Methods for Identification of Pilot Describing Functions From Closed Loop Operating Records", NASA TN D-6235, 1971.

11. McRuer, D.,D. Graham, E. Krendel, and W. Reisener, "Human Pilot Dynamics in Compensatory Systems - Theory, Models, and Experiments with Controlled Element and Forcing Function Variations", AFFDL-TR-65-15, July, 1965.

12. Lynch, W.A., and J. G. Truxal, "Introductory System Analysis", McGraw-Hill, 1961.

REFERENCES

13. Miller, G.A.,"The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information", The Psychological Review, vol. 63, No. 2, March, 1956, pp 81-97.

14. Kelly, D.H.,"Information Capacity of a Signal Retinal Channel", IRE Transactions on Information Theory, April, 1962, pp 221-226.

15. Pierce, J.R. and J.E. Karlin, "Reading Rates and The Information Rate of a Human Channel", The Bell System Technical Journal, March, 1957, pp 497-516.

16. Rink, R.E., "Optimal Utilization of Fixed-Capacity Channels in Feedback Control", Automatica , Vol. 9, pp 251-255, 1973.

ORIGINAL PAGE IS
OF POOR QUALITY

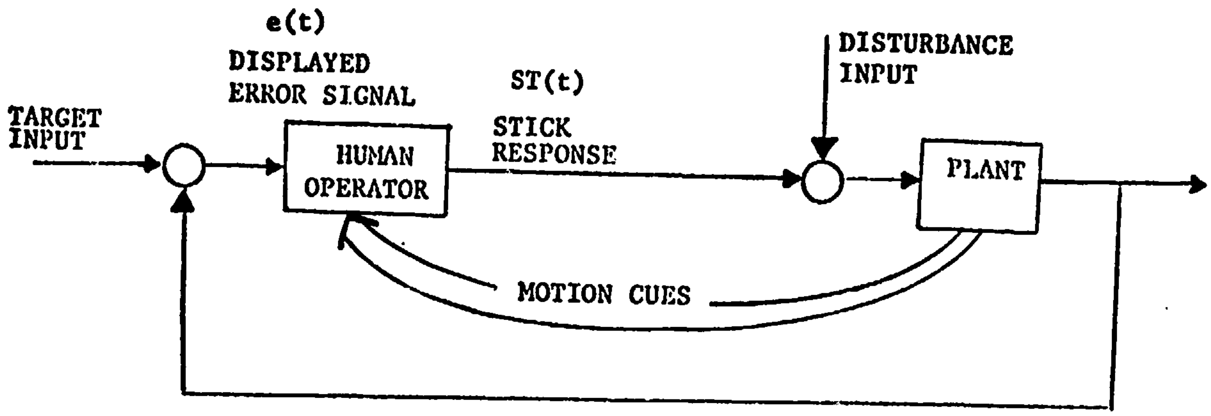

FIGURE (1a) -90° Motion Tracking

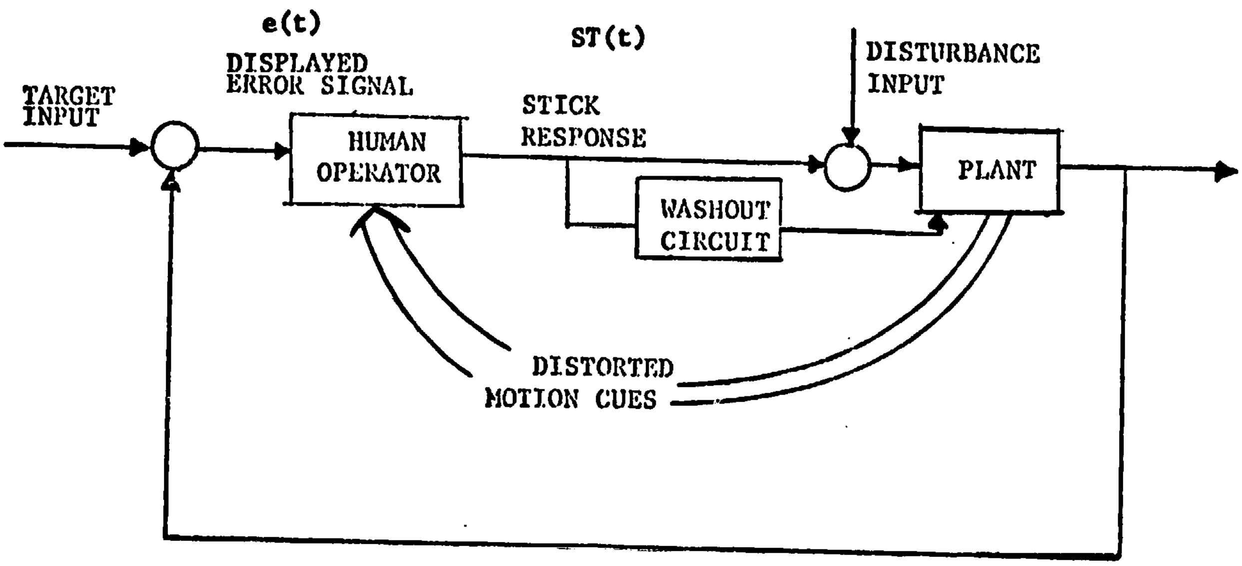

FIGURE (1b) -0° Washout Circuit

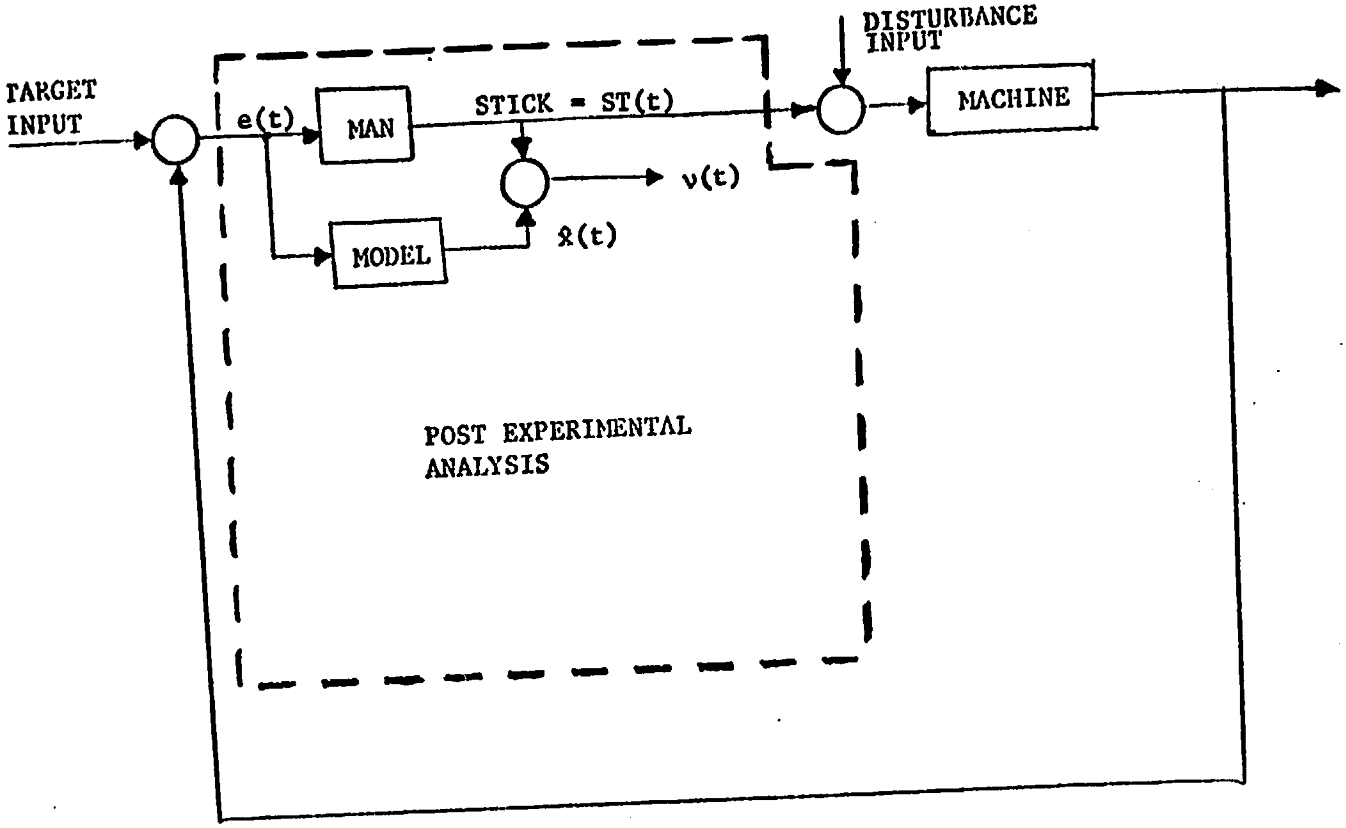

FIGURE (2)

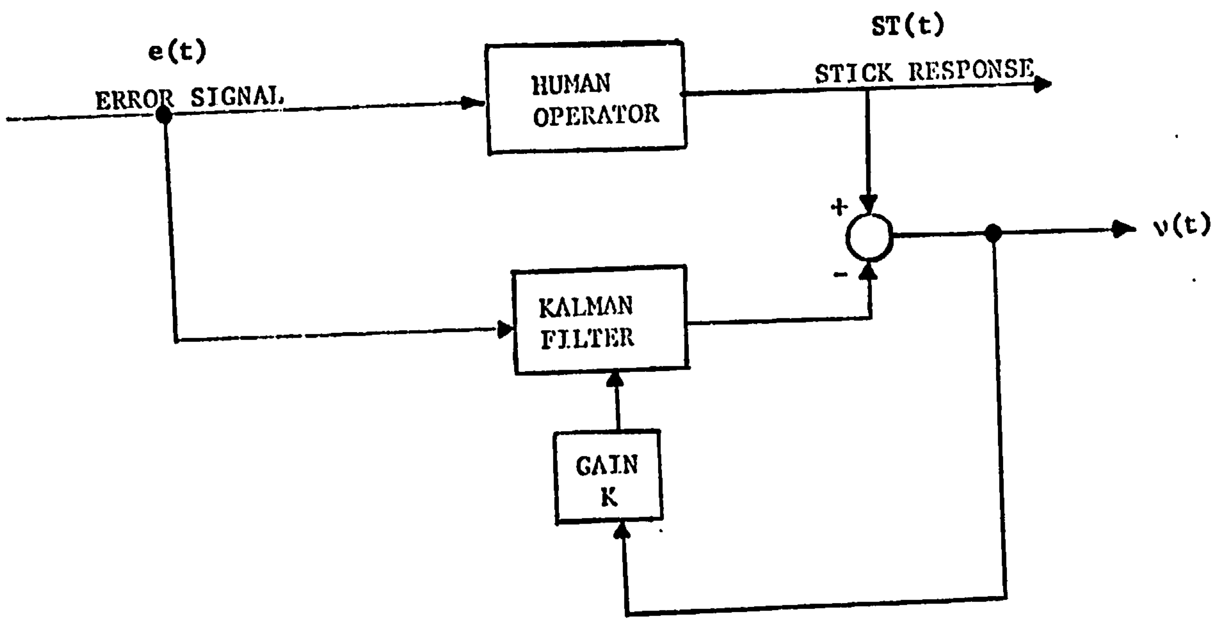

FIGURE (3)

ORIGINAL PAGE IS
OF POOR QUALITY

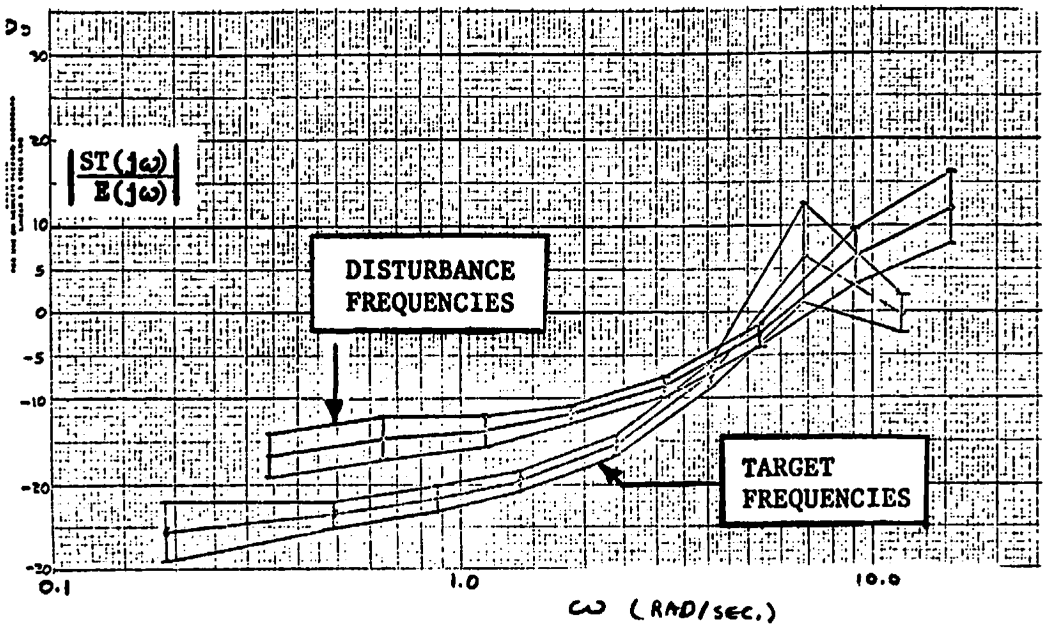

FIGURE (4) - The Human Operator Describing Function
0° Motion Case

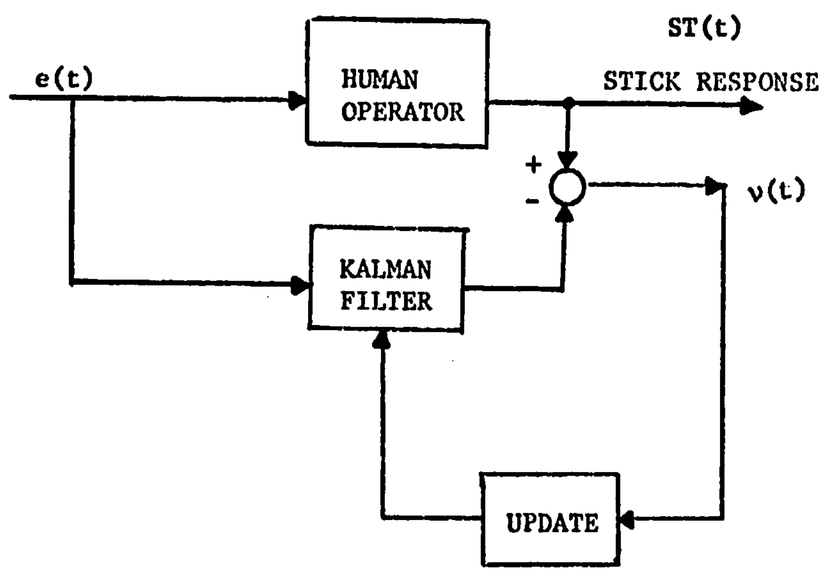

FIGURE (5) - Calculation of Subject Uncertainty

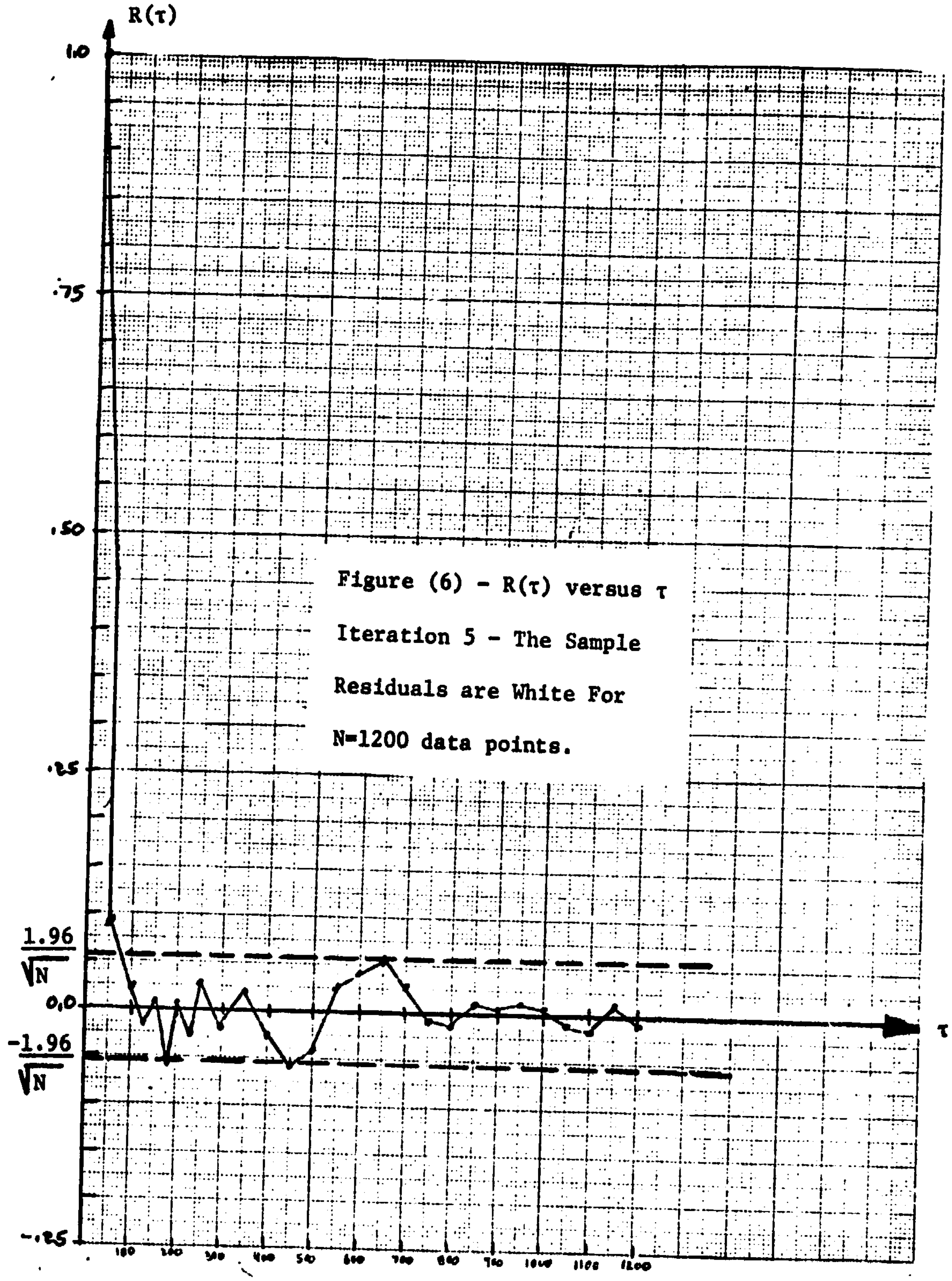

Figure (6) - R(τ) versus τ
Iteration 5 - The Sample
Residuals are White For
N=1200 data points.

ORIGINAL PAGE IS
OF POOR QUALITY

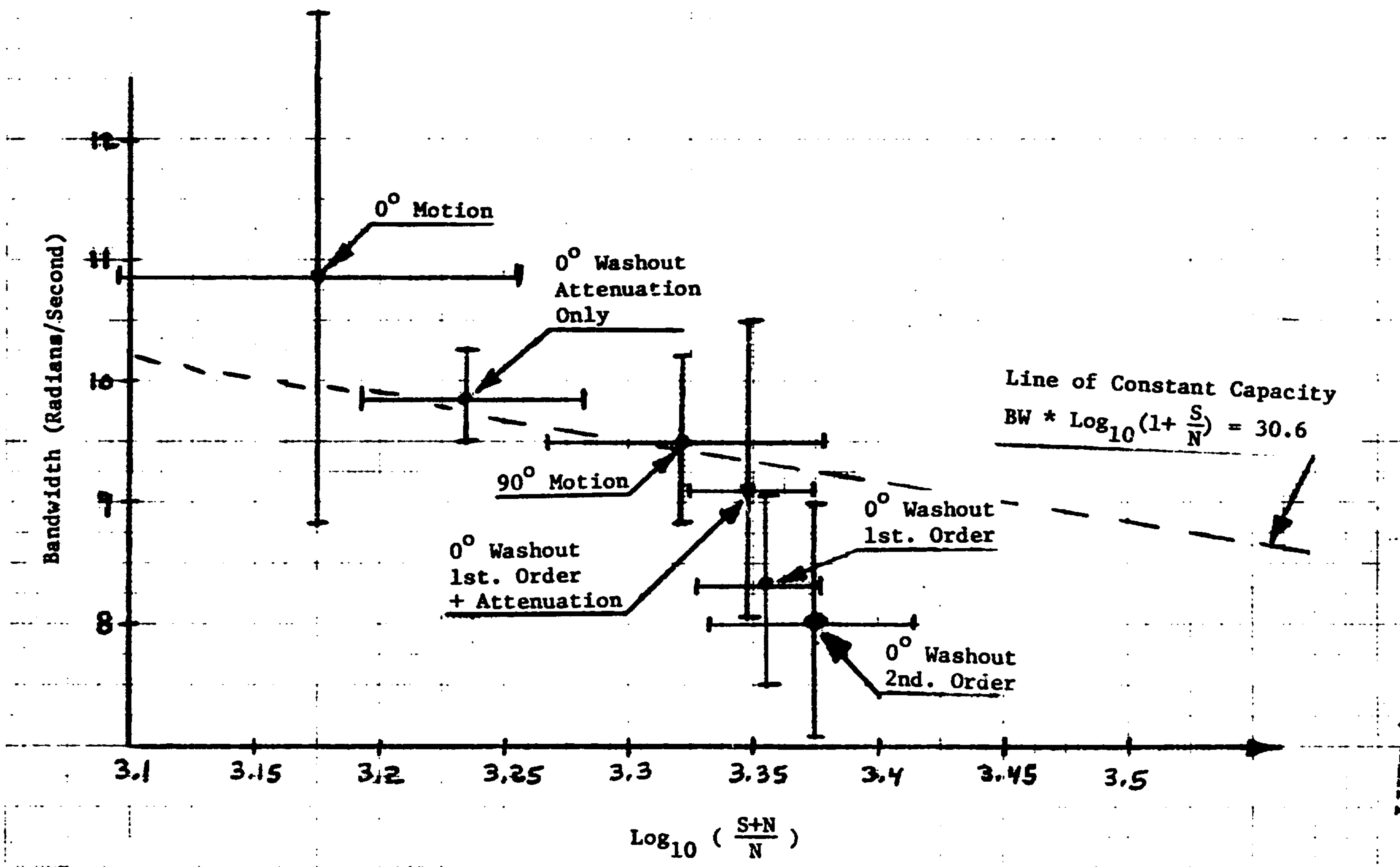

Figure (7) - A Diagram Which Allows Comparisons Between Simulators