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2. Development and Optimization of a Nonlinear Multiparameter Model for the Human Operator*

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A systematic method is proposed for the development, optimization, and comparison of controller-models for the human operator. This is suitable for any designed model, even multi-parameter systems. A random search technique is chosen for the parameter optimization. As valuation criteria for the quality of the model development the criterion function—the comparison between the input and output functions of the human operator and those of the model—and the most important characteristic values and functions of the statistical signal theory (mean values, auto- and crosscorrelation functions, histograms, and power density functions) are used.

A nonlinear multiparameter model for the human operator is being designed which considers the complex input information rate per time in a single display. The nonlinear features of the model are effected by a modified threshold element and a decision algorithm. Different display-configurations as well as various transfer functions of the controlled element are explained by different optimized parameter-combinations. The comparison with the well-known quasi-linear describing function for the human operator shows an essential superiority of the nonlinear model.

INTRODUCTION

For about 25 years models for the human operator as a vehicle controller have been developed. By this research method it was tried to reach the following two objectives:

(1) The capabilities and limitations of the human operator in manual vehicle control problems are to be measured and described as detailed as possible. Thus, valuation and design criteria are provided for the optimal—in the human engineering sense—layout of displays, controls, and automatic auxiliary controllers in integrated man-vehicle-systems.

(2) The human operator possesses features which today's technical systems are lacking extensively: adaptation especially to unforeseen situations, flexibility, capability to learn, and high reliability. By way of the analysis and simulation of these capabilities we find new automatic controllers which have the described features.

The specified objectives, especially the second, are set so high, that one only gets on smoothly with a systematic and economical procedure. This procedure should permit the development, optimization, and comparison of any controller-model for the human operator without time penalty. Simultaneously a reproducible method of test for the investigation of man/model-vehicle-systems is rendered possible with such a procedure. A recommendation of this kind has not been published up to now.

Both a method for the development, optimization, and comparison of controller-models and a nonlinear multiparameter model, which has been designed with the use of the previously mentioned method, are subsequently explained in more detail.

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METHOD FOR THE DEVELOPMENT, OPTIMIZATION, AND COMPARISON OF CONTROLLER-MODELS

Figure **1** shows the block diagram for the model parameter optimization in principle. The control of one output quantity is presented. Environmental disturbances shall in this case be excluded from the man-machine-system. From the indicated deviation, the difference between the desired value y_s and the actual value y_i, the human operator deducts a continuous stick signal which is transmitted through a control stick to the input of the controlled element, the simulated vehicle. Through information preprocessing by means of an additional prediction display, which indicates the future state of the vehicle y_v, the control effectiveness for the man-machine system is improved (refs. **1** and **2).** Because of the required transparency, the computation of the prediction value has been omitted in figure **1.**

For the model-machine control loop the same forcing function y_s is used as for the man-machine control loop. The difference between the stick signals of the human operator and the model is minimized. The chosen criterion function is proportional to the mean square error:

$$F(\underline{P}) = \int_0^T (z_V(t) - z_M(t;\underline{P}))^2 \, dt. \tag{1}$$

The optimization interval T corresponds to the duration of test and equals one minute.

For the parameter optimization a random search technique with local and global search algorithm is used (refs. **3** and **4).** Rastrigin (ref. **5)** has shown that these techniques are especially suitable for the optimization of multiparameter systems because of their high speed of convergence. Furthermore these techniques allow the criterion-hypersurfaces to be of very complicated shape. In nonlinear optimization problems in which discontinuities can be found in the criterion function, no difficulty results using random search techniques (ref. **6).** These are essential advantages as against the gradient techniques.

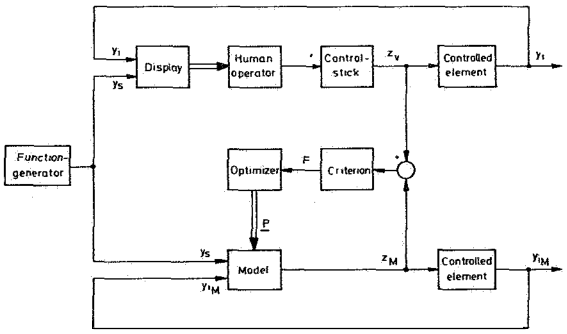

FIGURE 1.—Block diagram for the model parameter optimization in principle.

The optimal procedure for the development and optimization of controller models is best illustrated by a block diagram (fig. **2).** During "human operator in the loop" tests all input and output functions of the human operator are stored on magnetic tape. If various models are to be designed, the same stored time functions of these tests are used for their parameter optimization.

First the model is optimized as a transfer element in the open control loop (fig. **3).** Thereby the model is supplied with the same input functions which the human operator perceived

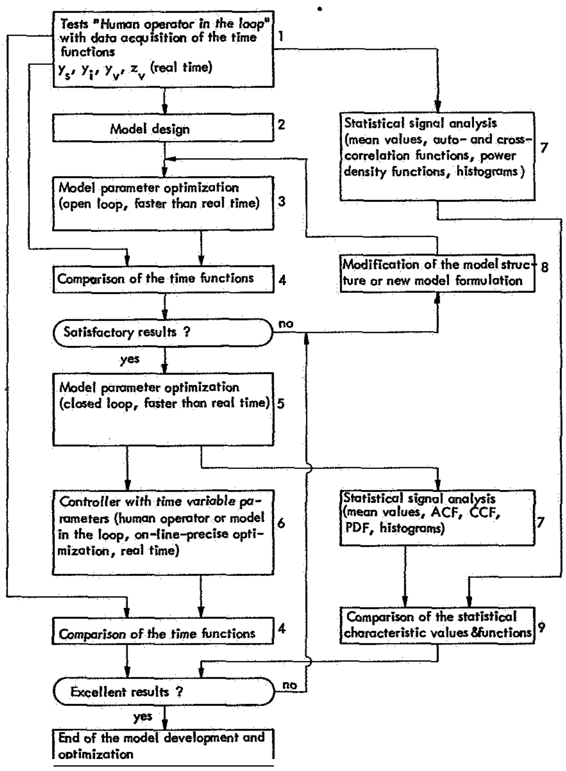

FIGURE 2.—Block diagram for an optimal procedure for the development and optimization of controller models.

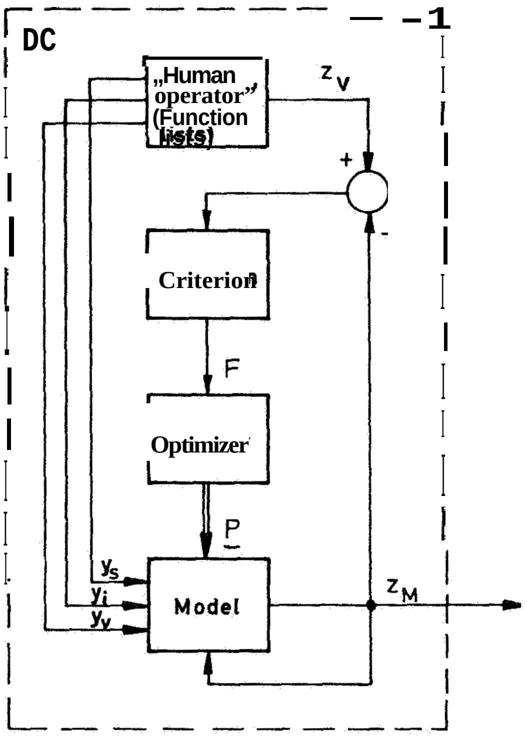

FIGURE 3.—Block diagram for the parameter optimization of the model in the open control loop.

through his sense organs. As manual control tasks are dynamic processes of low frequency they should be run in real time only, if the control is carried out completely or partly by subjects. Therefore, as there are no subjects in the control loop during model parameter optimization the programs shall be run faster than real time.

The time functions of the optimized open loop, plotted with a multichannel recorder, are compared with the corresponding time functions of the "human operator in the loop" tests. Mainly the stick signals (but also the deviations) are used for this coarse valuation criteria. If the comparison does not prove satisfactory, a modification of the model structure has to be considered or a new formulation of the model has to be adopted.

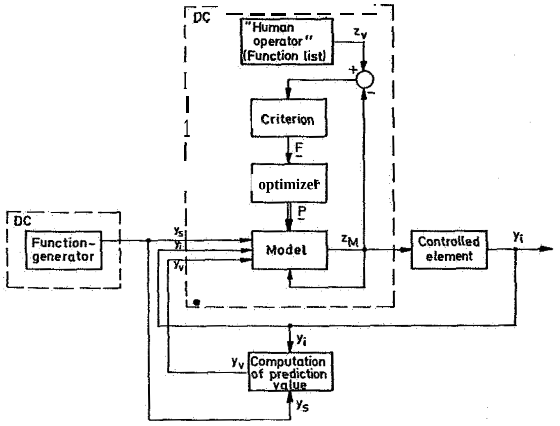

FIGURE 4.—Block diagram for the parameter optimization of the model in the closed control loop.

Whenever the model does not produce exactly the same output signal as the human operator after a satisfactory comparison of the time functions—and that will generally be the case—it must be examined whether the control loop, into which this model has been inserted as a controller, is stable. That is to say the remnant, the difference between the stick signals of the human operator and the model, is filtered by the controlled element and then included in the input information of the human operator (see fig. 1). With that, it is equally included in those of the model during the optimization of the open loop. In the closed loop this remnant is missing. Therefore it is necessary to continue the model parameter optimization in the closed loop (fig. 4). That is even then convenient, if the control loop is stable, because the criterion function does not necessarily reach its minimum at once, due to the missing remnant, although the optimization of the open loop previously led to a minimum.

The time functions of the closed control loop at the end of the over-all model parameter optimization are once more compared with those of the "human operator in the loop" tests. Additionally, a comparison of the corresponding statistical characteristic values and functions is now made. These are mean values, auto- and crosscorrelation functions, power density functions, and histograms. They have proved suitable for the valuation of man-vehicle control loops (refs. 7 and 8). If the results are excellent in comparison with well-known controller-models, the model-development and optimization is finished.

For the described simulation problems a hybrid computer system is best suitable. The used hybrid computer system consists of an analog computer Telefunken RA 770, a digital computer CAE C 90-40 (this corresponds with the SDS C 90-40), and an interface Telefunken **HKW 900.** It is programmed in Real-Time Fortran (ref. **9).** The method of test as well as the model-parameter-optimization are managed by standardized software. It allows in like manner the examination of controller-models which operate on analog, digital, hybrid, and other principles like threshold logic networks. Thereby only the exchange of subroutines is required. The separate systems of the man-vehicle control loop and the optimizer, which work according to the random search technique, are optimally distributed to the analog and digital component of the hybrid computer system. The controlled element, the computation of the prediction value, and the display-generator are realized on the analog computer. The digital computer produces a stochastic time function, which is used as the forcing function, and it calculates parameter change vectors for the random search technique from the sample values of an analog noise generator. The optimizer and the dominant part of the nonlinear controller-model are programmed on the digital computer too. If the well-known quasi-linear describing function for the human operator

$$G_{HO}(s)=\frac{K\cdot e^{-\tau s}}{1+T_N s}\cdot\frac{1+T_L s}{1+T_I s} \qquad (2)$$

is used, the controller is best simulated on the analog computer, except the dead time term.

The efficiency of the specified method is demonstrated by the development and optimization of a new nonlinear multiparameter model as well as by the comparison of this model with the quasi-linear describing function.

NONLINEAR MULTIPARAMETER MODEL FOR THE HUMAN OPERATOR

The complete nonlinear model for the human operator is shown in figure 5. A clear structure of the model is obtained by dividing it into five subsystems:

(1) The information perception system IP including multiplexer and analog-digital-converter **(ADC)**

(2) The modified threshold element

(3) The decision algorithm

(4) The summing element for the generation of stick signal increments

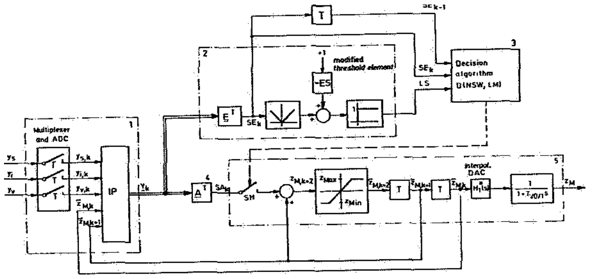

FIGURE 5.—Block diagram of the nonlinear model for the human operator.

(5) The system for the synthesis and output of the stick signal.

In the nonlinear model, contrary to most of the known mathematical models, the physiological aspects **of** the human controller characteristics are considered. If the sensory and neuro-physiological foundations of manual control are reflected upon, it is realized as one of the most important features of the central nervous system, that parallel information processing takes place already during the perception (ref. **10).** A great number of information is received by the sense organs, especially by the visual apparatus, and it is optimally combined for decisions, which lead to controller output commands for the hand. The complex information, which is included in a single display, is weighted by the nonlinear controller-model. Different display-configurations yield a different input information rate per time not only for the human operator but also for the model. Not only visual but also proprioceptive information is used in the model.

The visual information of the input vector

$$Y_k=\left(\begin{matrix} y_{s,k}\\ y_{sp,k-1}\\ e_{i,k}\\ e_{ip,k-1}\\ e_{v,k}\\ e_{vp,k-1}\\ \tilde{z}_{M,k+1}\\ \tilde{z}_{Mp,k}\end{matrix}\right| \qquad (3)$$

is the desired value $y_{s,k}$, the actual deviation

$$e_{i,k}=y_{s,k}-y_{i,k}, \qquad (4)$$

the predictive deviation

$$e_{v,k}=y_{s,k}-y_{v,k}, \qquad (5)$$

and the first derivations of these three time functions. These derivations attend to the human prediction capabilities (refs. **11** and **12).** Through the extension of the information rate per time up to a maximum of eight input functions the model differs essentially from all existing models. The multiplication of $\underline{Y}_k$ with the transposed weighting vectors $\underline{E}^T$ and $\underline{A}^T$ gives the scalar products

$$SE_k = \underline{E}^T \cdot \underline{Y}_k \tag{6}$$

and

$$SA_k = \underline{A}^T \cdot \underline{Y}_k. \tag{7}$$

These represent the result of an information reduction.

A modified threshold element and a decision algorithm (fig. 6), which has two parameters *NSW* and *LM*, define the nonlinear features of the controller-model by operating the switch *SH*. Sudden stick signal changes as well as constant stick deflections over longer time intervals are possible. Moreover the model temporarily possesses a linear transfer attitude, if a suitable decision is made depending on the overall input information rate.

Threshold elements are simplified models for the neurons of the human brain (ref. **13).** They are used as classifiers in automatic pattern recognition (ref. **14).** During manual control, dynamic patterns are recognized and analysed. Consequently it is logical to insert threshold elements into controller-models for the human operator.

The nonlinear model possesses a maximum of **19** parameters: twice eight weighting parameters, the threshold values *ES*, and the two parameters of the decision algorithm, *NSW* and *LM*. Thus, the parameter vector is

$$P = \begin{pmatrix} \underline{E} \\ \underline{A} \\ ES \\ NSW \\ LM \end{pmatrix}. \tag{8}$$

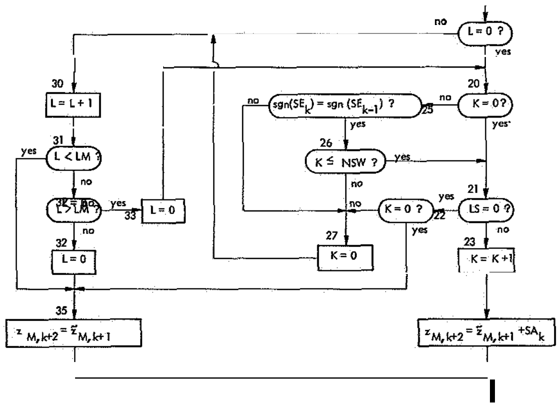

FIGURE 6.—Flow chart for the decision algorithm.

The generated stick signal $z_{M,k+2}$ is limited according to the mechanical stops of the control stick in use. It is then delayed for two sample intervals, and smoothed by an interpolating digital-analog-converter with a series-connected first order lag term.

RESULTS

Four different display-configurations are studied to show the different weighting of the single input functions. The difference between the compensatory and the pursuit tracking as well **as** the meaning of the prediction display can be read from the weighting factors of the controller-model. The additional information, which is given through the indication of the desired value during pursuit tracking, is scarcely used by the subjects, whereas an additional indication of the prediction value is weighted considerably. This result corresponds to the improvement of control effectiveness, which can be achieved by the application of the prediction display in tests with a human operator. Moreover the chosen structure of the model explains the human control action for various transfer functions of the controlled element. The parameters of the model were optimized for the control of two acceleration systems, one rate and one position system.

Subsequently only the results for an acceleration system with the transfer function

$$G_S(s) = \frac{1.6}{s^2(1+0.4s)} \tag{9}$$

are considered. The subject *S* controls the system **1** of equation **(9)** using the display-configuration **I** (pursuit tracking, additional prediction display). Therefore this test is marked with **S1I.**

From the comparison of the nonlinear model with the quasi-linear describing function for the human operator it is determined that the stick

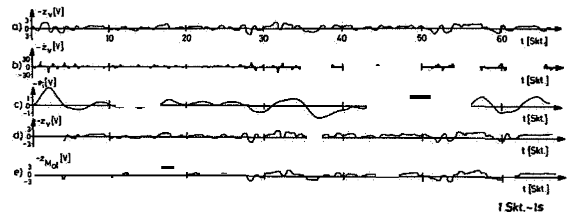

Figure 7.—The time functions of the S1I test. (a) and (d) Stick signal of the subject in the closed loop; (b) first derivation of the subject's stick signal; (c) actual deviation for (a); and (e) stick signal of the nonlinear model in the open loop.

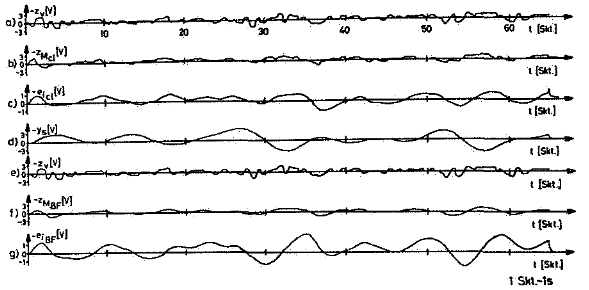

Figure 8.—Additional time functions of the S1I test. (a) and (e) Stick signal of the subject in the closed loop; (b) stick signal of the nonlinear model in the closed loop; (c) actual deviation for (b); (d) forcing function; (f) stick signal of the quasi-linear describing function in the closed loop; and (g) actual deviation for (f).

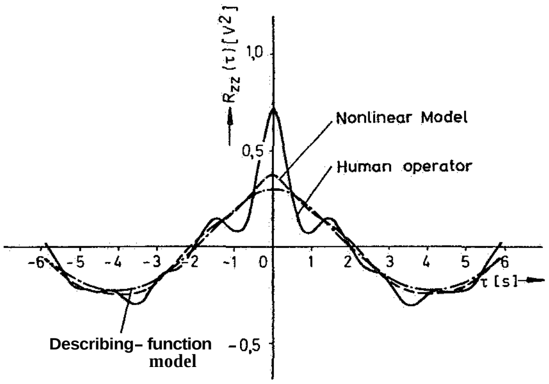

Figure 9.—The autocorrelation function of the stick signal for the S1I test.

signals of the nonlinear model in their fine structure look more like those of the human operator than the stick signals at the output of the linear transfer element (figs. 7 and 8). The autocorrelation and power density functions (figs. 9 through 12) as well as the histograms of the deviation and

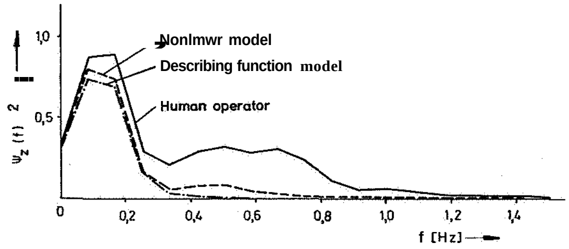

Figure 10.—The power density function of the stick signal for the S1I test.

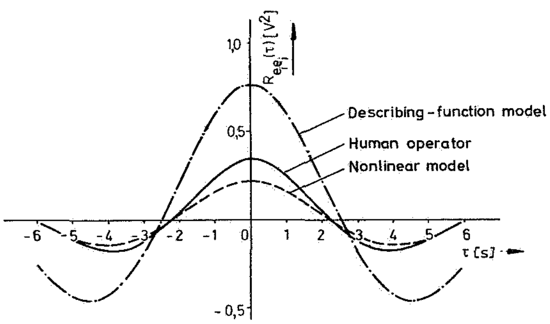

Figure 11.—The autocorrelation function of the actual deviation for the S1I test.

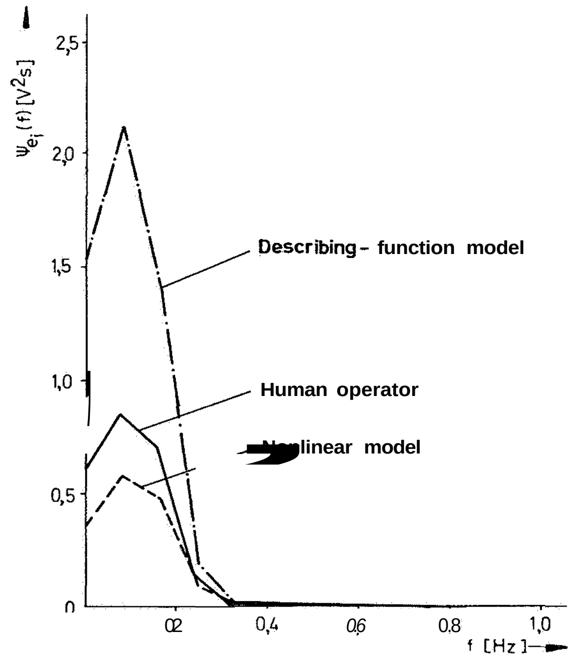

Figure 12.—The power density function of the actual deviation for the S1I test.

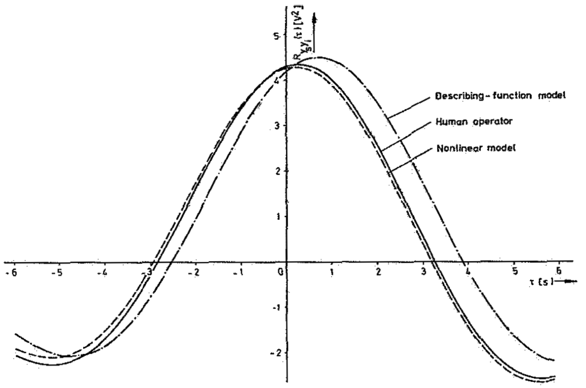

FIGURE 13.—The crosscorrelation between the input and output function of the control loop for the S1I test.

the stick signal show an essential superiority of the nonlinear model over the describing function. This is well marked by the control with an additional prediction display, because the nonlinear model possesses separate inputs for the prediction value and its first derivation. The crosscorrelation functions between the desired and actual value show too, that the control effectiveness is improved by the nonlinear model (fig. 13).

CONCLUSIONS

An efficient method for the development, optimization, and comparison of controller-models for the human operator was accomplished. An instrument is available to facilitate and accelerate the investigation of manual multiloop control and of the learning and adaptive features of the operator.

By using a heuristic approach the illustrated nonlinear multiparameter model has been designed which considers the complex input information rate per time and the information reduction in manual control as well as decision capabilities of the human operator.

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