Parameter estimation of a human controller transfer function in man-machine system using the PSO algorithm

Jelena Bulatović, Filip Gašparić, OliveraTomašević, Boris Knežević, Nikola Jorgovanović

Abstract—**Quantification of human behavior has always been quite interesting and very challenging task for control engineers at the same time. What might seem as an automated action performed by a humanrepresentsin fact an expression of complex underlying body and brain processes. Considering man's ability to memorize, adapt and learn,this task sounds even more difficult. Regardless of the non-linearity in human behavior which results from reasons listed above, some classical procedures have proved to be useful in practical application, and engineers have derived quasi-linear mathematical models which describe a human controller in closed-loop man-machine systems. In this work, a general form of these models was used and parameter estimation was performed. In the observed closed-loop system, a human controller was replaced with a corresponding system which contained estimated parameters. The performance of parameter estimation was measured using mean absolute error, when comparing the output of an actual system, controlled by a human, and a simulated one.**

Index Terms—**man-machine interface, human-controller, parameter estimation, particle swarm optimization**

I. Introduction

Man-machine interface (MMI) also known as Human-machine interface (HMI) is an integral part of certain devices or systems that allows user inputs to be translated as signals for machines that provide the required output. It has been widely used in electronic, medical, entertainment, military, aerospace and automotive industries etc. Understanding human physical, behavioral and mental features are essential when designing these systems in order to provide realistic and natural interaction with other systems and subsystems. Building describing functions and modeling the performance of human using linear differential equations allows prediction and evaluation of stability of the man-machine system. In research done so far, this has proven to be a very sophisticated problem. Beside the reason mentioned above, describing human behavior is also done in order to completely replace a human operator with an automated system.

The first complete model of a human as an operator in man-machine systems was described in a two-part paper [1][2]. The authors gave a detailed mathematical interpretation of human behavior in the role of a controller in MMI. All experimental techniques used to obtain such a model are discussed in [1]. Similarly, spectral analysis methods were used to obtain frequency domain mathematical models of the operator's behavior while performing manual tracking with tactile displays in [3]. The input-output and input-error cross-power spectral densities were obtained by a method of averaging modified periodograms. Their ratio represents a describing function of the human operator which analytic form was closely approximated using visual fitting. In [4] application of modern control concepts and estimation theory has been made to develop a model of humanoperator in manual tracking. It was applied to the prediction of human response in some simple, single-axis control tasks. The basic assumption was that the human operator behaves as an optimal controller, in accordance with his/her inherent limitations and task definition. The cascade combination of a Kalman filter, a least mean-squared predictor and a set of gains acting on the estimated state formed the resultant model and its unique features were the mathematical representation of the human's limitations and the resulting compensating elements. Later, in [5] the model proposed in [4] was used to analyze a more complex control situation, namely the manual control of the longitudinal position of a hovering aircraft.

In work described in this paper, it is assumed that the form of the subject's transfer function is known and we are not focusing on finding it. The idea is to place a human controller into a closed-loop control system and observe his/her behavior while performing different compensatory tracking tasks, which require different control strategies. Hence, our main goal is to estimate the parameters of the transfer function of a described human regulator in MMI using the PSO algorithm as a key step, which includes simple principle and offers fast convergence and computation.

Motivation for this work is better understanding of human behavior in man-machine systems in order to integrate human into complex technological systems or even completely replace with a certain automated system. As mentioned in [1],

Jelena Bulatović is with the Faculty of Technical Sciences, University of Novi Sad, 6 TrgDositejaObradovića, 21000 Novi Sad, Serbia (e-mail: jelena996@uns.ac.rs).

Filip Gašparić is with the Faculty of Technical Sciences, University of Novi Sad, 6 TrgDositejaObradovića, 21000 Novi Sad, Serbia (e-mail: filip.gasparic@uns.ac.rs).

OliveraTomašević is with the Faculty of Technical Sciences, University ofNovi Sad, 6 TrgDositejaObradovića, 21000 Novi Sad, Serbia (e-mail: olivera.tomasevic@uns.ac.rs).

Boris Knežević is with the Faculty of Technical Sciences, University of Novi Sad, 6 TrgDositejaObradovića, 21000 Novi Sad, Serbia (e-mail: borisknezevic@uns.ac.rs).

Nikola Jorgovanović is with the Faculty of Technical Sciences, University ofNovi Sad, 6 TrgDositejaObradovića, 21000 Novi Sad, Serbia (e-mail: nikolaj@uns.ac.rs).

one of the limiting factors in making a human operator model is that, beside a quasi-linear transfer function, correlated linearly with the forcing function, it also consists of a residual output which represents all output content which cannot be ascribed to a linear operation on the input. In this work, the remnant will be neglected, and we will focus on finding parameters of a quasi-linear model.

II. The Method

An input signal subject is tracking is shown on a computer monitor as well as the output of the controlled system. In each trial during the experiment, the subject moves the joystick up and down in order to minimize the difference between input and output signal which he observes through the visual feedback. Finally, recorded input and output signals are stored and used for parameter estimation of a human controller transfer function. Functional block diagram of a closed-loop control system with respect to visual stimuli describing the experiment setup is given in Fig. 1.

A. *Subjects and Experimental Design*

The experiment was performed by 5 healthy subjects (3 males and 2 females, 24.8 ± 1.5 years) after signing the consent form which was approved by the local ethical committee. The experiment involved recording the subject's response for 120 seconds when operating a given system.The reference signal, i.e. the forcing function *r(t)*, was multi sine whose frequency components ranged between 0.1 and 0.4 Hz and their amplitudes were randomly chosen in range 0 to 2.5.

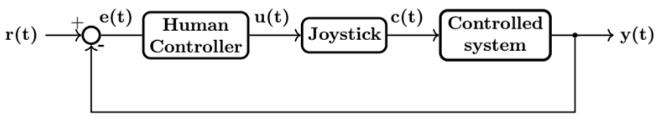

Fig. 1. A block diagram describing closed-loop system where human has the role of a controller; *r(t)* represents the forcing function, i.e. reference signal, *e(t)* is the system error, *u(t)* is the human controller output, *c(t)* is input of a controlled system and *y(t)* represents the output of the controlled system.

B. *Experimental protocol*

The forcing function was shown to the subject on a computer monitor and his/her task was to follow its motion using the joystick. It can be considered that the transfer function of the joystick used in this experiment is equal to one, i.e. *u(t) = c(t),* since this joystick does not contain elastic and inertial elements that can affect its behavior in the observed frequency range. The signal at the joystick's output *c(t)* represents an input signal for the controlled system which was modeled by one of four transfer functions of considered systems. The *y(t)* is the output of the controlled system which was also shown to the subject on the computer monitor.All the time during the experiment, the subject wasmonitoring the forcing function and the output signal on the same graph. The subject himself estimated the error as a difference between two observed signals and simultaneously corrected his/her control in order to minimize the error. This type of control is called compensatory tracking, because the reference signal *r(t)* appears randomly and the only information displayed to the operator is an output of a controlled system *y(t)* and it represents a visual feedback to the operator. An example of a subject performing the tracking task is shown in Fig. 2.

Transfer functions of systems controlled by the subject in this experiment and general form of a transfer function of a human controller when controlling the corresponding system are given in Table I. The experimental data considered for these systems were taken directly from the efforts of investigators in [1] [2] and [7].

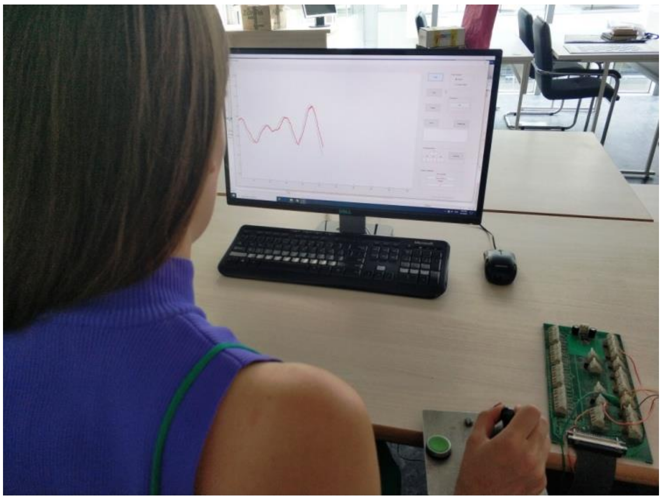

Fig. 2. A subject performing the tracking task using the joystick.

In order to perform the experiment, a personal computer (PC), a Hall-effect joystick and an acquisition card – National Instruments PCI-6024 were used. Data acquisition, as well as a simple graphical user interface that allows the user to run the experiment, were implemented within the MATLAB software package (ver. R2018a, Math Works, USA). The application gives the user the ability to enter data about the subject, set the duration of the experiment and parameters of a system operator controls as well as monitor tracking performance, data acquisition and calibration.

Reference signal *r(t)*, control signal *c(t)* and output signal *y(t)* are stored in the *.mat* file with data about the subject and parameters of a transfer function of acontrolled system. All recorded signals were sampled with a period of *T = 0.01s*.

III. Parameter Estimation

After the signals were recorded, parameters of a transfer function of the human controller were estimated. As mentioned above, the PSO algorithm was used for parameter estimation.

Swarm-based methods such as the PSO algorithm are well-known as powerful tools for dealing with the global optimization problems encountered in engineering [6]. PSO algorithm starts by creating initial population in a form of set of particles often called "swarm", and searches the space which contains potential solutions. Each particle is characterized with its position in previous and current iteration. In addition, each particle is able to remember its best achieved position through iterations, as well as swarm is able to remember best position achieved by any particle in that particular swarm. Because of the rules that define the process of their motion, particles will eventually swarm around the best possible solution. The generalized PSO algorithm used for the purposes of this work is presented in [6].

As an optimization criterion, mean absolute error was defined and the goal was to find parameters so that the value of this function is minimal. This means that the output of a simulated system needs to be as similar as possible to an actual output of a system obtained during the experiment. In a simulated system, the human controller is replaced with a system whose parameters are estimated. The number of particlesand the maximal number of iterations used in this work varied depending on the number of estimated parameters and it was set to be 10 and 100 times greater, respectively. For example, when the subject controlled system 1, the number of parameters that needed to be estimated was 3. Thus, the number of used particles was 30 and the maximal number of iterations was 300. It has been determined experimentally that this number of iterations is quite sufficient for the algorithm to converge towards the best possible solution for this particular optimization problem. Therefore, the stop criterion was the maximum number of optimization iterations. Out of 10 runs of parameter estimation algorithm, for each subject in every experiment, the run with the best available values of parameters for the given criterion was chosen.

TABLE I
TRANSFER FUNCTIONS OF SYSTEMS USED IN EXPERIMENT AND GENERAL FORM OF A HUMAN CONTROLLER TRANSFER FUNCTION WHEN CONTROLLING THE CORRESPONDING SYSTEM

System	Transfer function of a controlled system	Transfer function of a human operator
1	1	$K\frac{1}{\left(\frac{s}{a}+1\right)}e^{-s\tau}$
2	$\frac{1}{s+1}$	$K\frac{\left(\frac{s}{b}+1\right)}{\left(\frac{s}{a}+1\right)}e^{-s\tau}$
3	$\frac{4}{s}$	$K\frac{\left(\frac{s}{b}+1\right)}{\left(\frac{s}{a}+1\right)}e^{-s\tau}$
4	$\frac{2}{s(0.25s+1)}$	$K\left(\frac{s}{b}+1\right)e^{-s\tau}$

IV. RESULTS

The optimal parametersof a human controllertransfer function, when controlling systems 1 to 4that were obtained using the PSO algorithm are given in Tables II to V, together with the values of the corresponding criterion function (CFV) and mean absolute error (MAE). Mean absolute error is used to represent quality of human performance while performingcompensatory tracking task, that is, the average difference between the reference signal and the control signal during the experiment.Fig. 3 and Fig. 4 show performance of subject 3 during tracking an input signal while controlling system 1 and system 4, respectively.

TABLE II
PARAMETERS OF A TRANSFER FUNCTION OF A HUMAN CONTROLLER WHEN CONTROLLING SYSTEM I

Subject	MAE	K	a	τ	CFV
1	0.256	4.798	1.016	0.193	0.133
2	0.228	5.711	1.098	0.240	0.168
3	0.286	2.861	1.686	0.268	0.141
4	0.247	6.416	0.439	0.495	0.268
5	0.178	7.800	0.957	0.208	0.127

TABLE III
PARAMETERS OF A TRANSFER FUNCTION OF A HUMAN CONTROLLER WHEN CONTROLLING SYSTEM II

Subject	MAE	K	a	b	τ	CFV
1	0.307	4.806	1.966	2.418	0.333	0.148
2	0.355	1.117	1.162	0.354	0.377	0.199
3	0.395	1.230	2.454	0.849	0.409	0.148
4	0.368	3.852	7.985	26.757	0.252	0.236
5	0.280	5.945	1.593	2.615	0.316	0.165

TABLE IV
PARAMETERS OF A TRANSFER FUNCTION OF A HUMAN CONTROLLER WHEN CONTROLLING SYSTEM III

Subject	MAE	K	a	b	τ	CFV
1	0.382	0.830	3.312	2.340	0.331	0.248
2	0.468	1.006	7.513	22.169	0.248	0.317
3	0.418	1.091	2.495	12.415	0.008	0.270
4	0.417	1.290	3.620	4.779	0.301	0.332
5	0.566	0.901	2.955	2.594	0.366	0.457

TABLE V
PARAMETERS OF A TRANSFER FUNCTION OF A HUMAN CONTROLLER WHEN CONTROLLING SYSTEM IV

Subject	MAE	K	b	τ	CFV
1	0.540	1.837	0.324	0.186	0.382
2	0.695	1.241	0.341	0.078	0.481
3	0.409	1.730	0.173	0.205	0.274
4	0.401	1.637	0.158	0.206	0.272
5	0.621	1.216	0.082	0.002	0.403

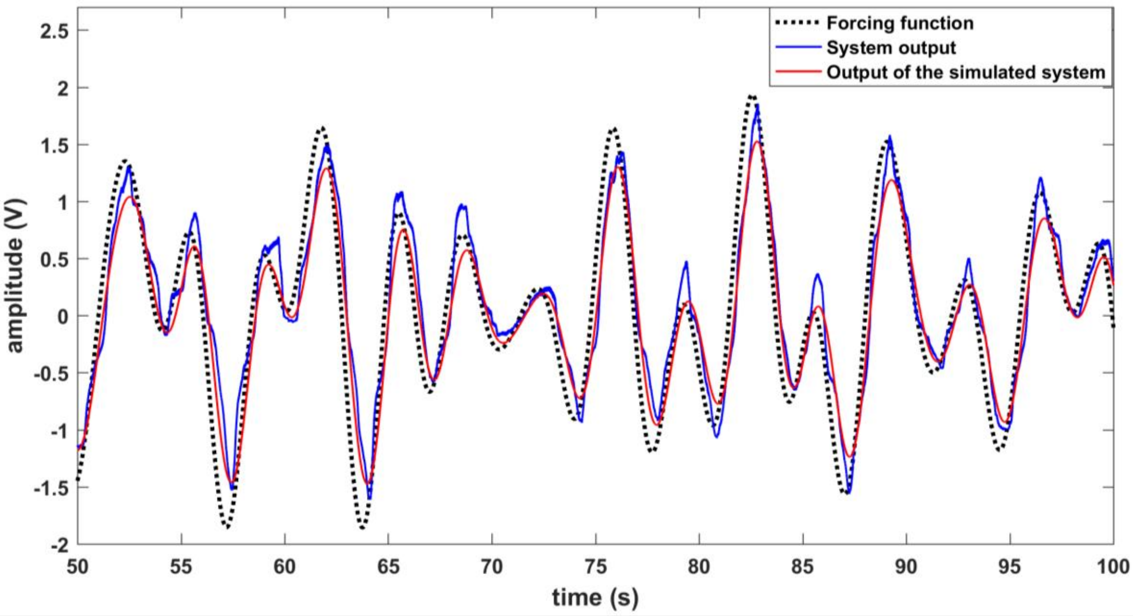

Fig. 3. 50 seconds of the experiment is shown: the input signal (black dotted line) subject 3 is tracking using the joystick and the output signal (solid blue line) which represents the output of the controlled system 1. After these signals were stored and parameter estimation was done, the human controller was replaced with the system with estimated parameters. The output of the system obtained in described way is shown with solid red line.

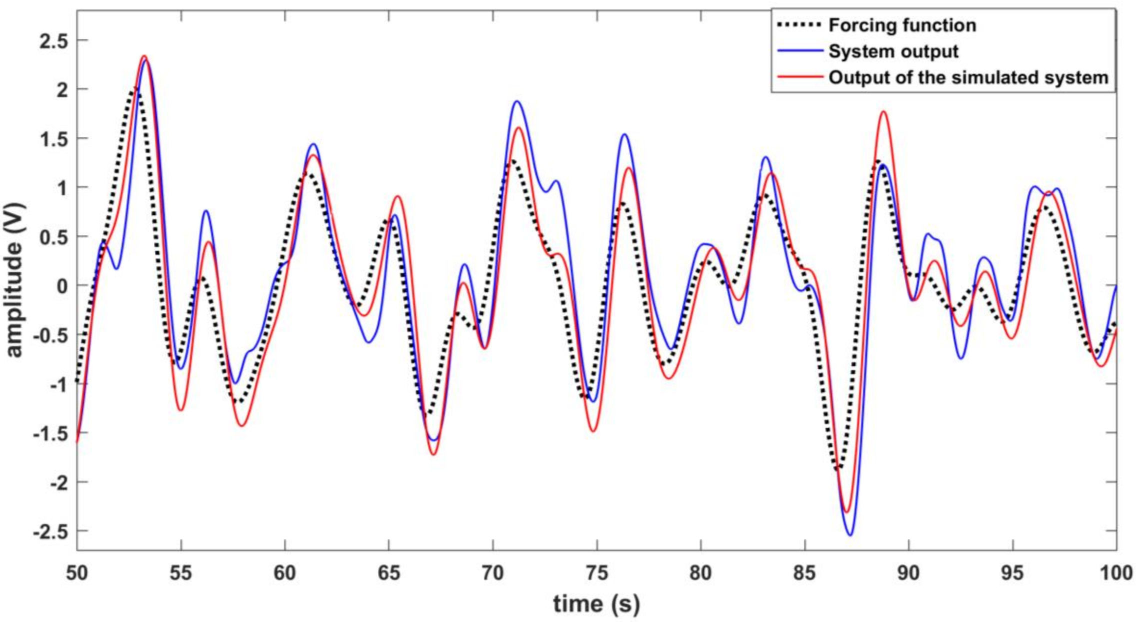

Fig. 4. 50 seconds of the experiment is shown: the input signal (black dotted line) subject 3 is tracking using the joystick and the output signal (solid blue line) which represents the output of the controlled system 4.After these signals were stored and parameter estimation was done, the human controller was replaced with the system with estimated parameters. The output of the system obtained in described way is shown with solid red line.

These graphs show the reference signal that the subject is tracking using the joystick, the output signal which represents the output of the controlled system and the output from the simulated system. As mentioned above, in the simulated system the human controller is replaced with a system with estimated parameters. Mean absolute error that subject 3 makes while tracking is 0.286 for the system 1 and 0.409 for the system 4. Clearly, system 4 is more challenging for subject to control due to its more complex transfer function (see Table I). Values of criterion function when estimating parameters are 0.141 and 0.274, for systems 1 and 4, respectively. Observing the results obtained from other subjects, it can be noticed that quality of parameter estimation depends on quality of subject's control.

V. Discussion

Although a human behaves as a non-linear system, a human operator shows some regular behavior from the controlled system viewpoint [8]. Also, a human has the ability to adapt to certain situations and remember patterns, but its behavior could be considered linear when no detectable pattern is present [9]. Although the forcing function consists of components at the same frequencies throughout the whole experiment, their amplitudes are numbers that range from 0 to 2.5, which are randomly generated at the start of each trial. This way, the subject cannot memorize the exact shape of the reference signal. The only thing a subject can learn is how to control the particular system.

It is natural to assume that it is not possible to obtain the same parameters for different subjects. Thus, it is expected that the subject's response will vary depending on several factors, such as the dynamics between the manipulated variable and the display, general condition and previous experience of the subject at the time of the experiment (which affects the subject's precision in control, reaction delays, etc.)[1]. Observing the human controller transfer function, it can be concluded how a subject behaves when operating a particular system.

The simplest way of control is modeled with gain K which gives an output signal proportional to the input signal. The next most obvious is reaction time of a human, modeled with$e^{-s\tau}$. When controlling the first threesystems, in transfer function of a human there is a lag, expressed by parameter$a$, showing that the human controller is able to follow slower changes of reference signal, and filters out faster ones, i.e. human behaves as a low pass filter. Lastly, the human's ability to predict a change in input and undertake corresponding control action is represented by derivative time, b.

Transfer functions of a human controller when controllingsystem 1 and system 2 obtained in this work can be considered appropriate for certain applications that do not require high precision, as the value of the criterion function varies from 5% to 10% of the maximum amplitude of the input signal. For systems 3 and 4, the calculated error was as twice as large and varied between 10% and 20% of the maximumamplitude of the input signal. This could be explained by the fact that these systems were more challenging for subjects to control, and thus evoked unexpected human behavior that could not be precisely described using only quasi-linear models. As stated in [9], experiments done by highly trained subjects will give the best results when estimating parameters of a human controller transfer function. Although the subjects who did the experiment for the purposes of this paper had certain time to get familiar with the way of controlling the given systems, they could not be classified as highly trained. This fact could be useful for further work in order to improve the performance of parameter estimation. The more reasonable solution would be to divide an experiment over several days, provide subjects with more training time and make longer pauses between trials in order to prevent mental and physical fatigue occurring in subjects.

VI. Conclusion

The work described in this paper gives an insight into a pilot study conducted with five subjects in order to test a new method for quantification of a human who has the role of the operator in a closed-loop control system. General forms of human controller transfer functions when controlling corresponding system were taken directly from existing literature and their parameters were estimated using the PSO algorithm. The results show that using this method it is possible to find parameters of a quasi-linear transfer function which is able to successfully describe a human behavior when controlling the given system. In further work, in addition to improvements mentioned above, dozens of subject should be considered for this experiment inorder to find a transfer function of an average human controller.

Because the experiment responded to the representation of an operator with a linear mathematical model in a closed-loop control system and examined the quality of visual feedback control, further steps in this research may include the use of another type of feedback, such as electro-stimulation or vibrotactile stimulation and to compare the quality of control when using different feedback, as well as to monitor whether the control can be improved by training. A functional description of human control could be crucial in various applications in biomedical engineering such as closed-loop upper limp prosthesis control, or for example, wheelchair control.

VII. Acknowledgment

This research was supported by the grants III41007 from the Ministry of Education, Science and Technological development of Serbia.

References

[1] McRuer, D.T. and Krendel, E.S., "The human operator as a servo system element part I". *Journal of the Franklin Institute, 267,* no.5, pp.381-403, May, 1959.

[2] McRuer, Duane T., and Ezra S. Krendel. "The human operator as a servo system element part II." *Journal of the Franklin Institute, 267,* no 6, pp.511-536, June, 1959.

[3] Schmid, H.P. and Bekey, G.A., 1978. "Tactile information processing by human operators in control systems0." *IEEE Transactions on Systems, Man, and Cybernetics, 8,* no.12, pp.860-866, Dec, 1978.

[4] Kleinman, D. L., Baron, S. and Levison, W.H., "An optimal control model of human response part I: Theory and validation." *Automatica, 6,* no. 3, pp.357-369, May, 1970.

[5] Kleinman, D. L., Baron, S. and Levison, W.H., "An optimal control model of human response part II: prediction of human performance in a complex task." *Automatica, 6,* no. 3, pp.371-383, May, 1970.

[6] Kanović, Ž.,Rapaić, M.R. and Jeličić, Z.D., "Generalized particle swarm optimization algorithm-Theoretical and empirical analysis with application in fault detection." *Applied Mathematics and Computation, 217, no.* 24, pp.10175-10186, Aug., 2011.

[7] McRuer, D. "Human dynamics in man-machine systems."*Automatica* 16, no.3, pp.237-253, May, 1980.

[8] Abe, M., *Vehicle handling dynamics: theory and application*., 2nd ed. Butterworth-Heinemann, 2015.

[9] Jagacinski, R. J., and Flach, J.M., *Control theory for humans: Quantitative approaches to modeling performance*., 1st ed. Boca Raton, Florida, CRC Press, 2003.