

A MAN AS THE REGULATOR IN MAN-MACHINE SYSTEMS

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Abstract. *The aim of the paper is to present the role of the human element in regularly used man-machine systems (MMS). From the technical point of view, it is possible to denote the human being and the machine as two components of one system. In the second part of the article, the authors introduce the results obtained through simulations of the human driver model; these simulations are focused on the quality of the control process. The structure of the model facilitates the detection and analysis of human error identifiers.*

Keywords

Control, high-risk system, human driver, man-machine system, regulator, simulation models.

1. Introduction

The human operator is a powerful, universal and effective regulatory element capable of solving unexpected situations quickly and adapting itself flexibly to the various operating conditions that characterize an MMS system. Based on his or her own experience, the human being executes and implements regulatory interventions, whose quality depends on the operator's knowledge and practice. In the described context, the human is a self-learning adaptive regulator with properties analogical to commercial regulators, which normally perform interventions based on mathematical description and analysis. However, there is a significant aspect of difference between the human operator and a commercial regulator: the human mind. This specific property enables the operator to integrate their brain, whose functions cannot be later excluded or overridden, into the regulation process.

2. Man-Machine Systems

Most machines are designed to be manipulated, managed, and controlled by humans. The man and the machine (a technical system) together form a specific higher system in which both these basic subjects cooperate and interact. In scientific literature, these systems are referred to as MMS. There are various types of human - machine interacting systems; from the simplest MMS such as hand tools, we can continue to mention the more complicated or specific ones represented by the car or the computer. An example of highly complex MMS systems can be seen in a nuclear plant or aircraft control.

In machines and devices, technical and economic parameters such as cost or sales prices are currently preferred to the significant aspects of safety and reliability. Thus, it is not possible to expect that an MMS system will operate and without any problems. From the perspective of safety, the system has to be designed in such a manner as to prevent major failures that could cause health risk, property loss, or ecological damage. Failures can be caused by either the machine or the human, who is not able to work and remain alert for an unlimited period of time; therefore, in the latter case, it is necessary to avoid an incorrect operation or a wrong decision.

A multitude of mathematical methods are employed to analyse human reliability, and many sources are focused on this issue [1], [2], [3].

2.1. Operator Activity Levels in MMS System

The human operator in an MMS system performs working and controlling operations at various stages of difficulty. The knowledge and description of the operator are among the necessary preconditions for the creation of accurate MMS models, which facilitate the analysis of critical points and the detection of hazardous system states as well as wrong operator actions.

An understanding of the overall human role and the operating principles related to human activity within a system is required for the successful evaluation of the safety and reliability aspects and enables further advancement in the communication between a human being and a machine [3].

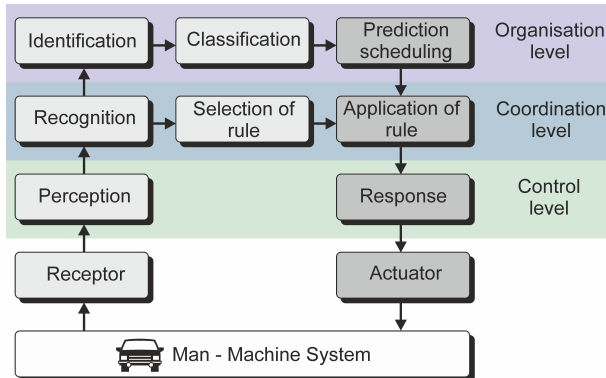


Fig. 1: Three levels of the human-based control according to Rasmussen's model.

Human activities in an MMS system depend on the specific difficulty aspects characterizing a system. The activities can be classified into categories (Fig. 1) based on these different difficulty aspects, which include elements such as the time and the function. The most widely applied classification approach was proposed by Professor J. Rasmussen, who categorized the human activities by difficulty criteria and the operator body parts used to carry out a given activity [4]. The discussed approach comprises the following levels:

- The control level, where a human being assumes the role of the regulator to perform regulatory activities and machine-controlling interventions. The active and executive elements of the human regulator are his or her kinetic devices such as the upper and lower limbs. This activity level is characterized by the smallest intellectual requirements; the human being performs his/her role to function as an executive element.
- The coordinating level, which comprises activities based on controlling a specific machine. The human operator must recognize several states of the controlled system, analyze the situation, and select a relevant activity to make the actual state of the system conform to specific rules, standards and techniques. The human is required to learn these activities in advance. The operator employs his or her brain to conduct a large number of trained states including specific and task-related activities, procedures, or methods. After many repetitions of one activity, the human being adopts the stereotype and learned practice; this is the stage when the operator “disconnects” his/her brain from the activity.

- The cognitive level, also known as the tactic level, includes activities related to decisions or analyses of unexpected and abnormal situations (system states) to which no specific action has been assigned yet. Other similar activities comprise the processes optimizing the selected human-preferred criteria, rush decisions (such as the reaction to an unexpected situation where the solution depends on the human experience, knowledge, and abilities). Within the described activity level, the human brain is activated: the operator incorporates his/her own mind into the system control procedures [5].

2.2. The Reliability of an MMS

Previous evaluations of MMS reliability focused principally on technical subsystems, and the influence of the human factor on the system reliability was not quantitatively monitored. The necessity to start new research in the field of the human factor and reliability arose from failures in nuclear power plants, chemical factories, and frequently repeated air and sea disasters. The scientific research has shown that it is very difficult to design universal evaluation procedures, mainly because human activities are markedly diversified. Each such activity comprises specific working methods which cannot be unified or merged, and thus it is not possible to label them with corresponding tabular values. Technical and human reliability are two aspects incompatible especially as regards data processing and the procedures of achieving a goal.

Humans actively use their brains and mind to set or complete certain aims and objectives, and their behaviour is generally directed towards achieving a goal. Based on the analysis of the current state, the human operator may choose tools and methods other than those recommended or ordered. The operator is capable of permanent monitoring and modification of his or her behaviour; thus, he or she can effectively correct wrong steps performed earlier within the system operation procedure. At this point, let us note that although the probability of an error occurring in certain human activities can be very high, the completion of the given aim is usually not jeopardized. The references [4], [5], [6] define human reliability as the ability to perform a task flawlessly under certain conditions and within the stipulated time.

Quantitative evaluation of human reliability is based on the total probabilistic safety analysis (PSA) of the whole MMS [5]. This analysis also comprises human reliability assessment (HRA), which carries information regarding the following elements: the safety and readiness of the technical system with respect to human interventions; human faults in comparison with

technical faults; and the possibility of increasing the reliability and safety of the system.

Human Reliability Assessment (HRA) is the part of the reliability discipline where the human performance in operating actions is studied. Human reliability is usually defined as the probability that a person will correctly perform some system-required activity during a given time period (if time is a limiting factor) without performing any extraneous activity that can degrade the system.

Human Error Probability (HEP) expresses erroneous performance of an action during the observation period. The determination of HEP is based in particular on research studies of comparable activities (generic data) and on the observation of incorrect actions in the analyzed or similar MMS.

There exist many methods for human reliability probabilistic assessment [6], [7] that pursue identical goals. These techniques are as follows: quantitative analysis of human behaviour; identification of erroneous activities; and identification of weak points of the system carried out together with the formation of pre-conditions for suitable remedial steps. The best known HRA methods are THERP (Technique for Human Error Rate Prediction), SLIM (Success Likelihood Index Method), HEART (Human Error Assessment and Reduction Technique), ATHENA (A Technique for Human Error Analysis), and CREAM (Cognitive Reliability and Error Analysis Method) [8].

3. The Human Driver as a Regulator

Driving a vehicle is a complex activity. However, currently there does not exist any universal driver model capable of simulating the total of driving activities across all control levels (feedback control, coordination level based on the application of rules, knowledge-based cognitive level). Driver simulation models can be classified into two basic categories that result from the description of driving-related activities. These two classes based on the mode of vehicle driving are as follows:

- Transverse driving, which is defined by both the quality of road holding and the car position inside the traffic lane.
- Longitudinal driving, which is determined by the control of the car speed and acceleration in a linear direction.

The basic control circuit for the transverse compensation vehicle driving is shown in Fig. 2. The eye perceives the control process, and the information from

the visual field is transferred to the central nervous system by back coupling. The vehicle dynamics are represented by the transmission function $Y_M(p)$, and the dynamics of the human regulator are expressed by the transmission function $Y_H(p)$. The driver executes feedback control of the momentary transverse car location $y(t)$; the aim is to achieve a situation when the control divergence $e(t)$ is zero and the vehicle continues moving towards the desired position $y_z(t)$.

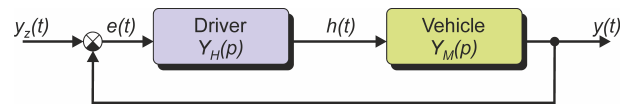


Fig. 2: A model of compensation vehicle driving.

In practice, as we have mentioned above, vehicle driving is of a complex character: It is a set of partial activities with different properties on the different control levels (Fig. 3). The memorized stereotypes and routine manoeuvres are realized by the R_{pg} precognitive controller based on knowledge, qualifications and idea processes. The ability of prediction, which facilitates the estimation of the future trajectory and situation on the roadway. The predictive controller R_ψ participates in the vehicle control. By this controller, the driver holds his car in the required direction $\psi_r(t)$.

The compensation controller R_y is used for the minimization of the control error $e(t)$. With this controller, the action interferences are controlled based on the visual information about the required location $y_z(t)$ and the actual location $y(t)$.

In feedback compensation vehicle control, the control circuit has the structure of eye – brain – hand and is defined by permanent feedback. The information is obtained predominantly from visual sensation, and its processing is performed in the corresponding centres of the gray cerebral cortex (ectocinerea). The functions of the feedback predictive controller R_ψ and the precognitive controller R_{pg} are suppressed; their action interferences are not a priority, and they participate in the control only minimally [9].

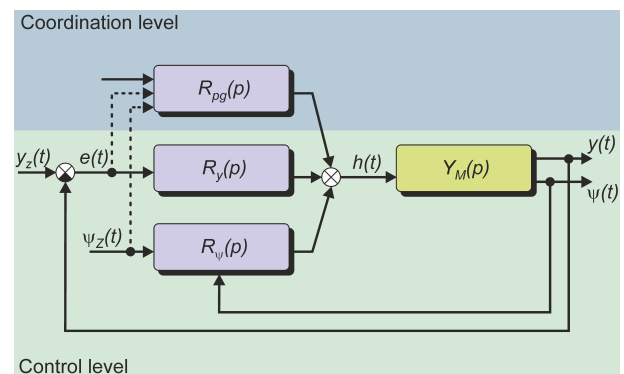


Fig. 3: Types of the driver controller [9].

3.1. Transfer Functions of the Human Driver

The transfer function of the driver may assume different structures depending on either the driver’s control abilities or the simplifying hypothesis to be applied.

The model of compensation vehicle control derived from the transfer of the open loop of the control circuit F_0 is denoted as the Crossover Model [12]. The different transfer functions $Y_H(p)$, $Y_M(p)$ are validated for every driver, vehicle and ambient conditions, but certain properties are invariable in different types of the control task. These properties can be defined as follows:

- The closed loop of the feedback control is stable if the driver manages his work. The unstable state occurs only in the case of control ability failure on the part of the driver.
- The frequency characteristic of the open loop crosses the frequency axis with slope of approximately -20 dB.

These transfer functions of the driver models are correct for small changes of the input signals and drive with low dynamics. The variables of the activator (driver $Y_H(p)$) are set to ensure convenient conditions for the open loop transmission $F_0(p)$ in equation Eq. (4); thus, the stability of the control system will be secured.

$$F_0(p) = Y_H(p) \cdot Y_M(p) = \frac{\omega_C e^{-T_D p}}{p}, \quad (1)$$

where F_0 - the open loop transmission, $Y_H(p)$ - transmission function of driver, $Y_M(p)$ - transmission function of vehicle, ω_C - cut frequency given by the product of the amplification of the system and the intensification of the action element, T_D - the driver response delay.

The simple form of the transfer function of the driver $Y_H(p)$ is expressed by formula Eq. (2) and applies to the compensation type of control [13], [14]. The action interferences of the driver $h(t)$ assume only an integrating role, and they are performed with a certain time delay given by the quantity of the driver delay T_d :

$$Y_H(p) = \frac{K}{p} \cdot e^{-T_D p}, \quad (2)$$

where T_d - the constant describing the delay of the driver response, K - the constant determining the size of the driver intensification.

The transfer function type shown below is presented very frequently [10], [11].

$$Y_H(p) = \frac{K \cdot e^{-T_D p} \cdot (T_a p + 1)}{(T_n p + 1) \cdot (T_I p + 1)}, \quad (3)$$

where T_D - the constant describing the delay of the driver brain response to visual sensation, T_n - the inertia constant determining the driver’s delay with respect to the activity of the neuromuscular system, T_a - the predictive constant associated with the driver’s practice, T_I - the counterproductive inertia delay associated with the learned stereotype and routine process, K - the attenuation describing the driver’s custom.

The form of the transfer function Eq. (3) results from the hypothesis that the driver behaves like a linear component. Some nonlinear components always occur in the real control circuit. The extended form of the transfer function of the driver $Y_H(p)$ is presented within equation Eq. (4) [14], and the nonlinearity of the action component is implicated in the remnant factor:

$$Y_H(p) = \frac{K \cdot e^{-T_D p} \cdot (T_a p + 1)}{(T_n p + 1) \cdot (T_I p + 1)} + \text{remnant}. \quad (4)$$

A very interesting form of the transfer function $Y_H(p)$ is shown in [15], where the driver model consists of two parts that contain two information inputs. The transfer function of the driver comprises two controllers (Fig. 4). The controller with the transfer function $Y_{Hy}(p)$ reacts to the respective divergence $e(t)$ of the vehicle location $y(t)$ and the second controller $Y_{H\psi}(p)$ reacts to the vehicle direction $\psi(t)$.

At this point, we may conclude that the complex forms of the transfer function faithfully represent the real behaviour of the driver or operator in MMS systems; it is also possible to say that the identification of the parameters of the transfer function forms is a difficult and problematic task.

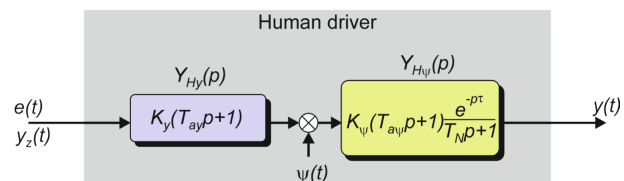


Fig. 4: A driver model with more inputs and transfer functions.

3.2. Simulations of a Nonlinear, Driver - Vehicle Model

The driver does not execute the control functions according to the linear model; rather than that, his or her actions are invariably encumbered with negative effects of nonlinear components, such as hysteresis, insensitivity, saturation, or nonlinear amplification.

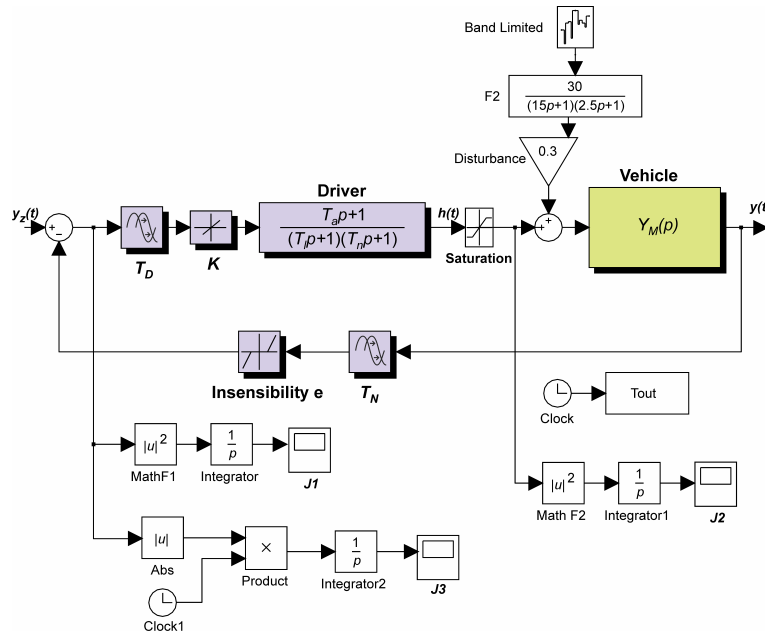


Fig. 5: The nonlinearity components in the driver - vehicle simulation model.

Compensation vehicle control is characterized by single feedback, where the driver feedback compensation controller is active. The nonlinear components can then be located in either the direct branch or the feedback, and they affect the vehicle control process in the manner described below.

- Insensitivity e is associated with the decision of the driver to respond to a situation by performing an intervention $h(t)$ depending on the actual car position $y(t)$.
- Saturation is located explicitly on the output of the action element in the direct branch, and it can be defined as the undesired limitation restricting the driver's intervention $h(t)$.
- Amplification K expresses such driver's response where the intensity of the intervention corresponds to the magnitude of the control deviation $e(t)$.

An example of possible location of nonlinearities in the control circuit of the driver – vehicle simulation model is shown in Fig. 5. The variant amplification K and the saturation of the driver's intervention are located in the direct branch; the nonlinearity of the insensitivity e is contained in the feedback.

3.3. Quality Criteria of the Control Process

The quality of the control processes in the driver – vehicle simulation models is determined by means of the following iterative criteria:

- Quadratic integral criterion used to classify the control deviation value $e(t)$ (marked by the symbol $J1$ in the simulation models).
- Quadratic integral criterion applied to classify the action intervention value $h(t)$ (marked by the symbol $J2$ in the simulation models).
- Integral criterion ITAE for the classification of the control deviation value $e(t)$ (marked by the symbol $J3$ in the simulation models).

The block diagram of the components for the calculation of the quadratic criteria in the simulation model is presented in Fig. 5. The numerical values of the integral criteria $J1$, $J2$ and $J3$ are generated by program algorithms based on circuit solution of the simulation model.

3.4. Simulation of the Parameters and Time Constants of the Human Driver Model

The simulations for different models of the **human driver – vehicle** system are implemented in Matlab 7.9.0. The aim of the simulations is to determine the influence of the parameter changes and time constants of the model driver transfer function $Y_H(p)$ on both the quality of the regulatory process. In the given context, it is also necessary to define what values can be used to preserve the stability of the control loop.

Thus, we specify the intervals of the values of the parameters monitored in the **human driver – vehicle** simulation models; the aim of the simulation was

to secure a stable regulatory process by obtaining the lowest possible values of the quadratic integral criteria $J1$ and $J2$, see Fig. 6.

3.5. Results of the Simulations

Changes of the time constants T_a and T_l , the transport delay T_D , and the value of the variable amplification K in the transfer functions of the driver $Y_H(p)$ are given in Tab. 1. Similar interval values of the analyzed parameters are reported in references [14], [12], [9].

The effectivity of the driver's intervention significantly depends on the amplification parameter K . If the intervention is performed with an insufficiently small or excessively large force, it will destabilize the entire regulatory system. This resulting effect is vital for the monitoring of the fatigue factor.

Tab. 1: The range of the simulated parameter values and time constants in a closed loop the with insensitivity e .

Parameter	Insensitivity e	
	Direct branch	Feedback
T_a [s]	1.0–2.0	1.0–2.2
T_D [s]	0.1–0.2	0.1–0.2
T_l [s]	0.20–0.41	0.2–0.5
e [m]	0.1–0.4	0.1–0.4
K [rad·m ⁻¹]	0.010–0.015	0.010–0.013

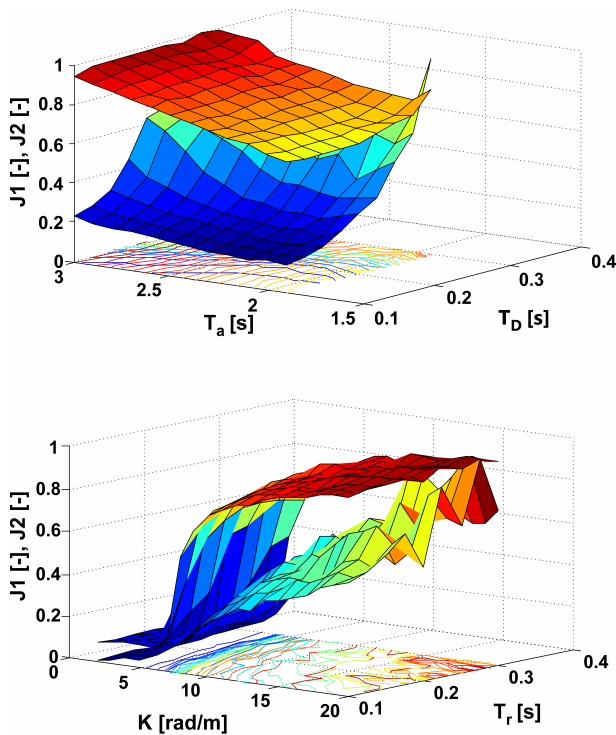


Fig. 6: The values of the integral criteria $J1$, $J2$ in the simulations of the time constants T_a , T_D , T_r and the variable amplification K .

4. Conclusion

The growing number of aeroplane crashes, chemical plant accidents, and disasters related to dangerous operations has led to increased interest in human functions within MMS systems. It follows from various detailed analyses of accident causes that most negative events of this type are based on a human factor failure.

The reliability of MMS depends largely on the human factor, and therefore it is very important to monitor any human activity in the system. The performed simulations of the **driver (man) – vehicle** nonlinear models showed that even small changes in the parameters of the transfer function of the human operator may destabilize the whole regulatory system and jeopardize its overall safety.

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