McRuer Models for Human-Machine Systems

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Abstract—This article is focused on modeling human-machine systems using McRuer models, particularly systems formed by human operator and a steering wheel. Result of the work are dynamical models of human operator corresponding to regulation of different systems and various system forcing functions. Different steering wheel stiffness was also measured to find its influence on the speed of human reactions.

Keywords—human-machine systems, human operator, McRuer models, steering wheel, stiffness

1. INTRODUCTION

According to [1], there are 3 main methods of modeling human operator. First are models based on control theory (McRuer models also belong here), second are models based on human psychology and finally models based on intelligence technologies. Within this paper, human operator will be described by control theory models as a linear time-invariable system. These models allow us to predict human behaviour.

2. MCRUER MODELS

McRuer models can be explained on a plain regulation loop shown on Figure 1, where F_R is the model of human operator and F_S is the regulated system.

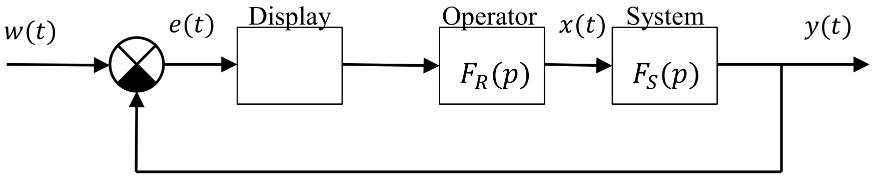

Figure 1: Regualtion loop [2]

The principle of the McRuer models can be simply described as a process, where the human operator adapts and changes his frequency response in order to achieve transfer function

$$F_0(p) = F_R(p)F_S(p) = \frac{K_0}{p} \cdot \mathrm{e}^{-\tau p}\,, \tag{1}$$

in the direct branch of the loop [2].

3. SIMULATOR AND EXPERIMENT

All measurements were taken with the vehicle driving simulator shown on Figure 2. The simulator was equipped with Logitech G920 steering wheel, through which the human operator was interacting with the system. Processing of the operator action (the rotation of the steering wheel in time), as well as implementation of the controlled system and indicator of the regulation error were realized in MATLAB Simulink environment. Before a measurement, operator tried the regulation of the given scenario a few times to get used to it. Subsequently 10 repeated measurements were made, from which an average operator model was estimated. All experiments were taken only with one operator though.

Figure 2: Vehicle driving simulator [3] and regulation error indicator

4. TESTED SYSTEMS AND FORCING FUNCTIONS

Two forcing functions were chosen for identification of the human operator: A *pseudo random binary sequence* (PRBS) and a periodic signal, in which several sin functions were combined. To allow the operator to prepare for the regulation, all forcing functions were multiplied by zero in the first second of the measurement. All measurements had the same length of 60 seconds. An example of the PRBS and periodic forcing functions are shown in Figure 3.

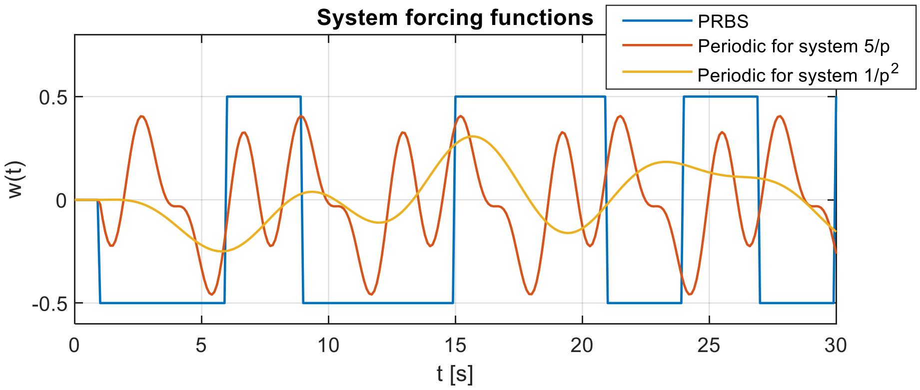

Figure 3: Forcing funcions used for the measurements

Table 1: Tested systems

General transfer function	Particular transfer function
K_S	10
$\frac{K_S}{p}$	$\frac{5}{p}$
$\frac{K_S}{Tp+1}$	$\frac{10}{p+1}$
$\frac{K_S}{p^2}$	$\frac{1}{p^2}$

Operator's responses were tested with the transfer functions shown in the Table 1. All systems were measured with the PRBS forcing function. In addition, the $5/p$ and $1/p^2$ systems were also measured with a harmonic forcing functions. Furthermore, the $1/p^2$ system was measured with two different stiffnesses of the steering wheel: with one that comes with the steering wheel by default and with no stiffness at all.

5. IDENTIFIED OPERATOR TRANSFER FUNCTIONS

For every scenario, the optimal transfer function describing the operator was found, i.e., the simplest mathematical description that could simulate operator's actions accurately enough. Table 2 lists the models of operator for various systems. These were obtained with default steering wheel stiffness. Responses to the system $1/p^2$ (measured under different conditions) are shown in the Table 3.

Table 2: Identified operator transfer functions

Controlled system	System forcing function	Identified operator transfer function	Theoretical operator transfer function [1]
10	PRBS	$\frac{0.1391}{p} \cdot \mathrm{e}^{-0.325p}$	$\frac{K_R}{p} \cdot \mathrm{e}^{-\tau p}$
$\frac{5}{p}$	PRBS	$0.1547 \cdot \mathrm{e}^{-0.58p}$	$K_R \cdot \mathrm{e}^{-\tau p}$
	periodic	$0.3853 \cdot \mathrm{e}^{-0.08p}$	
$\frac{10}{p+1}$	PRBS	$\frac{0.08(1.178p+1)}{p} \cdot \mathrm{e}^{-0.595p}$	$\frac{K_R(T_1p+1)}{p} \cdot \mathrm{e}^{-\tau p}$

Table 3: Identified operator transfer functions for $1/p^2$ system

Steering wheel stiffness	System forcing function	Identified operator transfer function (general)	Identified operator transfer function (particular)
Default	PRBS	$\frac{K_R(T_1p+1)}{T^2p^2+2\xi Tp+1} \cdot \mathrm{e}^{-\tau p}$	$\frac{0.0213(17.3p+1)}{0.5939^2p^2+2\cdot 0.269\cdot 0.5939p+1} \cdot \mathrm{e}^{-0.66p}$
	periodic	$\frac{K_R(T_1p+1)}{T_2p+1} \cdot \mathrm{e}^{-\tau p}$	$\frac{1.1999(2.461p+1)}{0.2899p+1} \cdot \mathrm{e}^{-0.325p}$
None	PRBS	$\frac{K_R(T_1p+1)}{T^2p^2+2\xi Tp+1} \cdot \mathrm{e}^{-\tau p}$	$\frac{0.0338(11.5565p+1)}{0.5019^2p^2+2\cdot 0.2398\cdot 0.5019p+1} \cdot \mathrm{e}^{-0.675p}$
	periodic	$\frac{K_R(T_1p+1)}{T_2p+1} \cdot \mathrm{e}^{-\tau p}$	$\frac{0.8279(3.1383p+1)}{0.3162p+1} \cdot \mathrm{e}^{-0.415p}$

Measured and estimated data from one measurement for the system $1/p^2$ are shown on Figure 4. Operator frequency characteristics for every measurement with this system are shown on Figure 5.

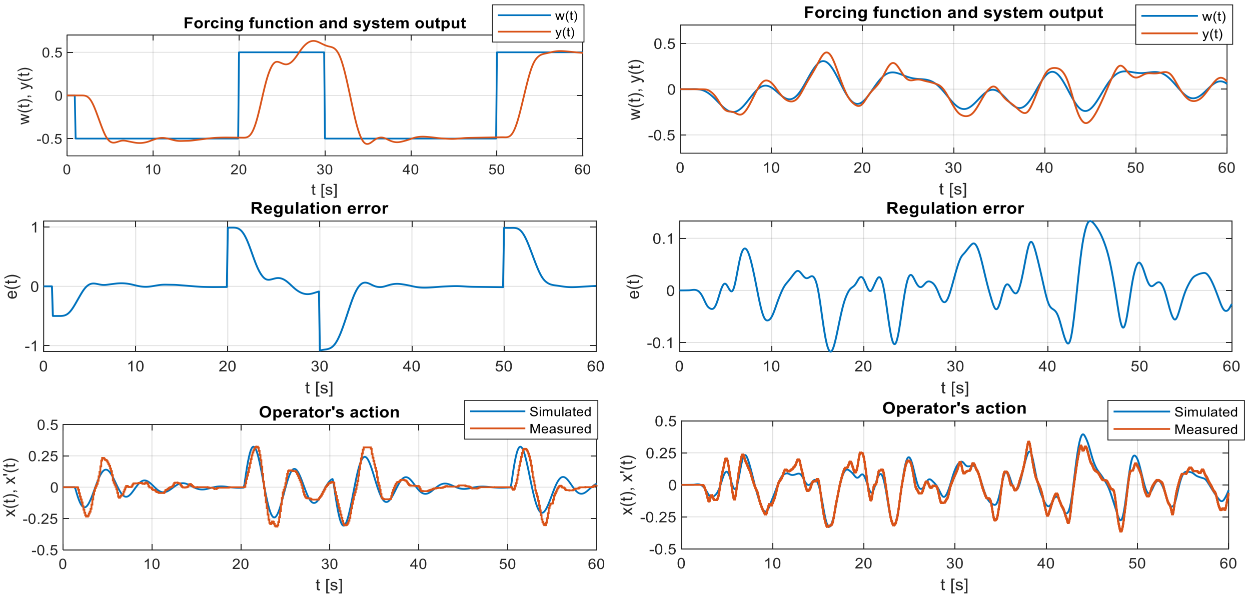

Figure 4: Example of measured and estimated data, $F_S(p) = 1/p^2$ with PRBS and harmonic functions

Transport delays couldn't be identified with high accuracy. For example, with PRBS forcing function, the `tfest` function used for identification gave similar percent fit to estimation data (about 50–60%) for transport delays spreading from 0.3 to 0.7 seconds. Direct estimation of reaction delay by the `tfest` function was not reliable. Therefore, model was identified with several delays and the model with the smallest error of the fit was used.

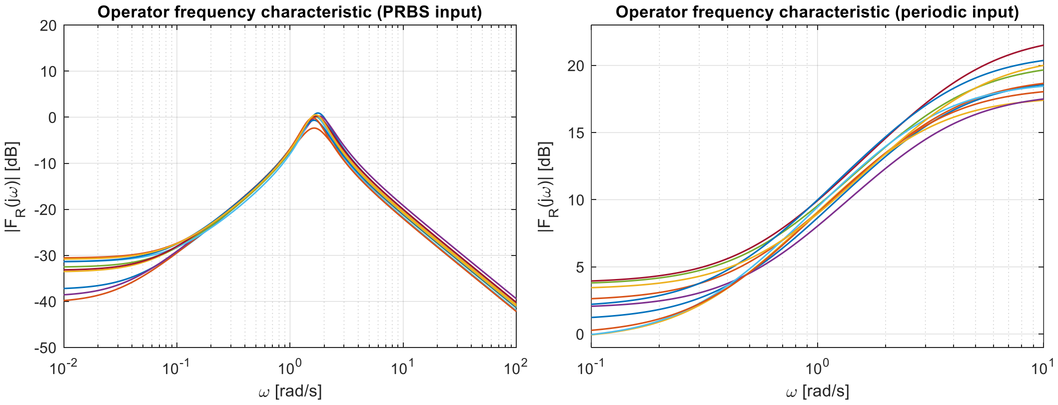

Figure 5: Operator frequency characteristics when regulating system $1/p^2$

6. CONCLUSION

For the simpler systems ($K_S, K_S/p, K_S/(p+1)$) observed operator responses were equal to McRuer theoretical assumptions. However, for the $1/p^2$ system the responses were different. That could be caused by the fact, that the theoretical regulator is $F_R(p) = K_R p \cdot \mathrm{e}^{-\tau p}$, which has no real-world equivalent.

Another discovery is that the optimal transfer function of human operator differs depending on the system forcing functions. For the $5/p$ system only the numerical value of coefficients differs, whilst there was a completely different formula in the case of the $1/p^2$ system.

With the different steering wheel stiffness experiment, another interesting result came out. There was a significant drop of the coefficients with the sinusoidal input and no stiffness. However, with the PRBS input, only a slight change of coefficients values was observed.

In general, identified operator transfer functions comply with McRuer models theory. However, individual coefficients are dependent on the system forcing function and the steering wheel stiffness. Next aim will be to estimate optimal wheel stiffness for given scenarios to achieve faster driver reactions and ensure higher safety in traffic.

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