20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

Instrument for the estimation of cognitive and motor control function of human movement

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Abstract **– A prototype of an experimental set-up has been built to identify human implemented motor-cognitive control function in a loop control task. Man-machine systems or systems where the human operator is embedded into the control loop (human-in-the-loop) are known and studied since the beginning of the cybernetics in the 60's of last century. Modern technologies permit to rediscover and reuse human regulatory models to be of help in many areas like sport performance evaluation and neurodegenerative diseases assessment.**

I. INTRODUCTION

Function of the hand in terms of skill, dexterity and ease of movement is often impaired after stroke accidents or in neurodegenerative diseases (e.g. Parkinson's or Alzheimer's disease) and in elderly people as well. The prototype developed in the medtech laboratory of HEIG-VD allows for the proposition to the subject of a series of tasks for testing hand's residual abilities and for training and helping the subject recovering from impairment.

More generally the system is part of an experimental set-up for studying human motor and cognitive performances using the tools and methods of the control theory for regulated systems.

A. The human-in-the-loop model

The term "human-in-the-loop" or HIL is used each time a complex system is controlled by a human operator so that the output of the system during its functioning is depending on the performance of the human operator which can be considered as part of the whole system. The most obvious example of a HIL system is a car and its driver. It is quite clear that the output of the system (intended in general as the vector composed of all the possible mechanical measures taken on the running car) is a function of the mechanical transfer function of the car and the control transfer function of the driver who is trying to follow, as closely as possible, a reference function (keeping the car at the center of the line at a

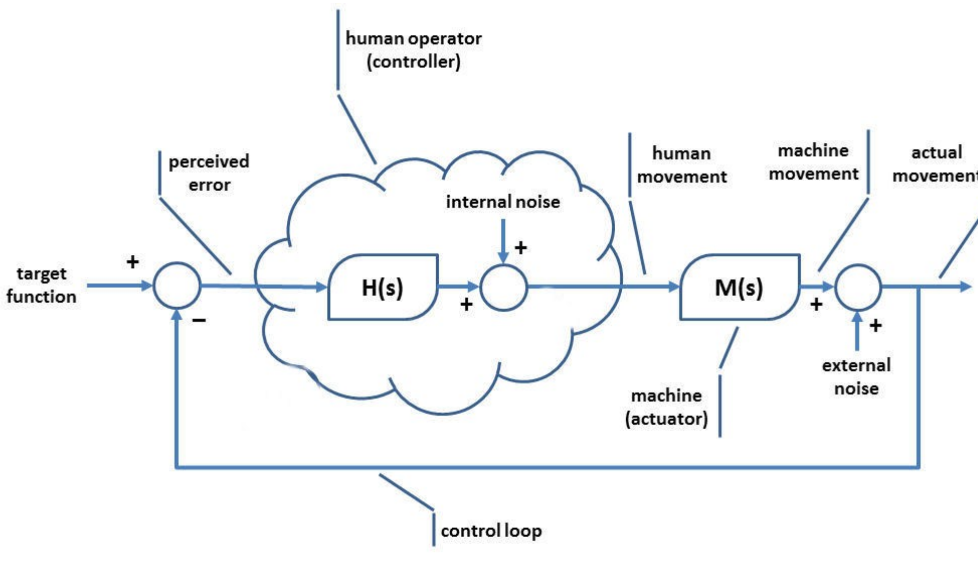

Fig. 1. Classical cybernetic control loop of a human operated machine.

ISBN-14: 978-92-990073-2-7

given speed), while managing constraints (acceleration, type of road, traffic) and noise (wind, road's floor). Many other examples can also be considered like operating a bulldozer or even a sport instrument (like a rowboat).

This approach is quite important in aviation as the control effort of the driver (pilot) in managing a complex machine like an aircraft may become overwhelming. In military aircraft piloting, where very demanding maneuvers are required at high speed and high acceleration in war conditions, the cognitive and motor performances of even the best of the "top guns" may prove to be inadequate. That's why the measure of the human cognitive performances is required to understand how much an aircraft can be effectively guided by a human being and thus to assess at what extent the human operator must be accompanied in parallel by an assistive computer [1]. As a matter of fact, unlike light aircrafts, most of the military air fighters of today, which are instable by conception (almost no-wing aircrafts or flying bodies), are impossible to be guided by a human alone without the assistance of powerful computers.

The simplest kind of HIL system, where a machine is guided by a human operator according to a defined target evolution, is depicted in Fig.1. The target function is the wanted behavior of the machine. This requirement may come from the human operator itself (closed skill) or from the external environment (open skill). The concepts of open and closed skills come from sport cognitive behavior. Free throws in basketball, serving in tennis or arrow aiming in archery are examples of closed skills sport activities. On the other end football and hockey sport gestures are largely depending on the external situation and thus are considered as open skills.

The difference between the desired machine movement (target function) and the actual machine movement is perceived by the human operator as an error and as a consequence the human will accordingly control the machine to recover to the right behavior. In doing this the human operator will implement a control function $H(s)$ (in the Laplace domain) and will have to cope with some internal noise (e.g. concentration, attentional state, drowsiness, drunkenness, disease). The output of the human operator is the human movement of a given part of the body which is used to guide the machine (hand on a handle or a steering wheel, foot on a pedal, etc.). This movement will not appear as such at the output of the machine as the machine itself will implement its behavior by means of its transfer function $M(s)$ producing at the output the movement of the machine (heading or direction of car). The machine output will also be influenced by the external noise (e.g. wind) providing the final and actual machine movement.

It is the task of the human operator that of minimizing the error between the target function (desired output) and the actual output of the machine in all possible situations and under various noise conditions.

The model in Fig. 1 is a quite simple indeed as just the linear hypothesis has been done. Actual models must also consider non-stationary or time varying control functions (e.g. fatigue) and non-linear behavior (e.g. thresholds). Furthermore the operator's function $H(s)$ in the simplified model is just considering the whole operator performance without separating the cognitive control function (central nervous system) and the motor control function (peripheral nervous system and muscular-biomechanical control function). The perception control function is not considered as well.

The scope of this model is that of having a reference conceptual framework for trying to identify the human operator control function $H(s)$ (e.g. its numerical

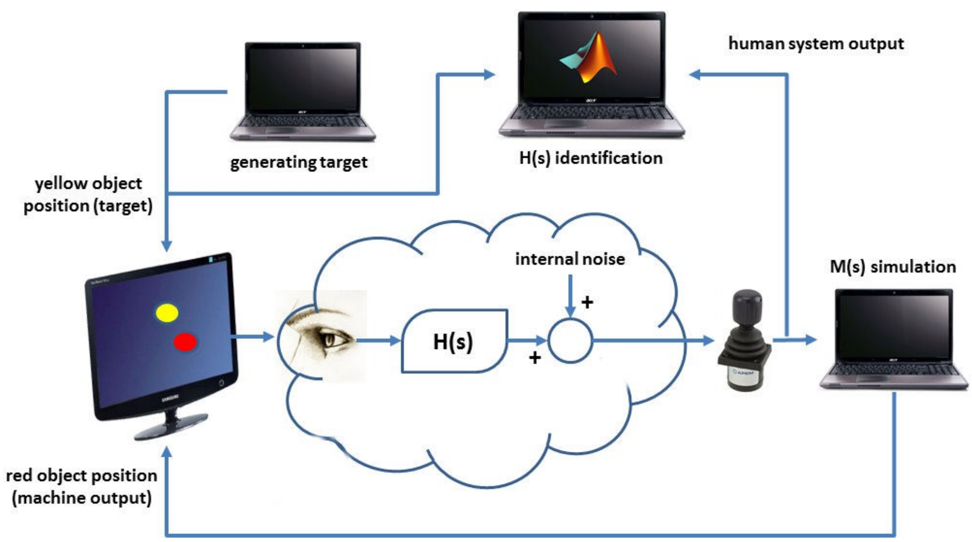

Fig. 2.Schematic of the experimental set-up.

parameters like poles or zeroes) such that each human operator might be classified and diagnostic conclusions might be derived from this evaluation.

Before going further into the presentation, it should have to be noted that the function $H(s)$ is just considering the human operator from the regulation system point of view without the possibility of inferring any consideration about the actual nervous system's parts (nervous centers) or pathways. While the $H(s)$ function is not to be intended as a mathematical description of any anatomical or functional part of the human body, nevertheless its identification might well be used as a classifier to evaluate subjects and to follow the evolution of their performances in sport training, in disease and in recovery from disease.

B. An experimental set-up for implementing a HIL model

It is clear that the function $H(s)$ which the human operator will implement in controlling the machine is depending on the function $M(s)$ of the machine itself. In other words the $H(s)$ is just one of the infinite number of control functions which the adaptive human being system can use. Thus, as $H(s)$ is in general depending on $M(s)$, we need to use a standardized and well known $M(s)$ if an experimental setup of the model has to be implemented.

To this end we considered a simple joystick interfaced to a personal computer. Normally the output of a joystick is linearly proportional to the angle of inclination of the stem of the joystick. Using a personal computer this linear function can be modified at will, so to implement any $M(s)$. Furthermore the external noise can also be easily added to the output.

In this way the human movement acting on the joystick can be transduced to the actual movement of the machine which is presented to the human operator as the position of a visual object on the computer screen. In this way the control loop is closed. A target function (target object) can be added on the screen (to implement an open skill task, e.g. a tracking task). Without a screen target, a closed skill task can be implemented as well.

A schematic of the experimental set-up is presented in Fig. 2. Although, for clarification purposes, in the figure three computers are shown, in practice only one personal computer, with an extension screen for the subject under test, is used for defining the $M(s)$, for the optional creation and presenting of the target object and for the acquisition of the human movement so that data are gathered for $H(s)$ evaluation by means of the MATLAB software (obtained from MathWorks, Natick, Massachusetts, USA).

II. THE HANDFORCE SYSTEM

The joystick is the only special and custom hardware part needed to implement the whole system. Although many ready to use USB (Universal Serial Bus) joystick devices are available on the market, we decided to build a custom one. This decision was taken on the need of having a complete control over the data arriving from the device and having the assurance of a predictable and precise timing (sampling frequency) for the data from the joystick [2] [3]. Moreover we also added a custom handle on the joystick with piezoresistive force sensors on it to also monitor the grasping force in real time. Although the chosen device has no force return feature, we put into the handle a vibramotor (similar to the vibrating actuator in mobile phones) for creating a somatosensory stimulation on the subject (useful in particular tasks). The concept schematic of this device is shown in Fig. 3. The joystick is a resistive three axes industrial rugged type (APEM 4000 model obtained from Pewatron AG, Zürich, Switzerland). The force sensors on the handle are piezoresistive elements (FlexiForce A-201 4.4 N model obtained from Tekscan Inc. South Boston, MA, USA). The vibramotor is a Nokia mobile phone spare part.

As all the sensors are resistive, a very simple signal conditioning and microcontroller interfacing was created by means of a series of monostable oscillators based on the NE555 (NE556) integrated circuit. The NE555 circuits are triggered in a circular fashion and they produce rectangular pulses of varying time duration. The time width of each pulse is measured with the timer device contained into the MSP430F169 microcontroller. The resolution of the measure is in 8^{th}s of a microsecond (as the clock frequency used for the timer is 8 MHz). The capacitor in the monostable circuit was chosen such as to limit the maximum pulse width to 2.5 ms so to obtain a

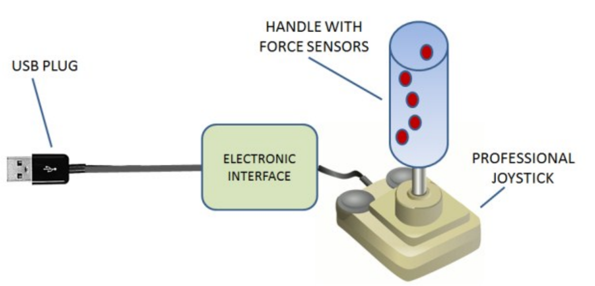

Fig 3. Schematic view of the new joystick.

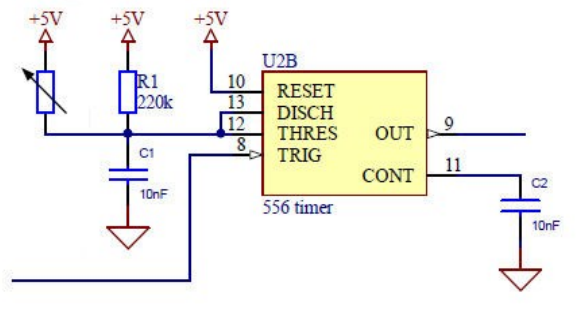

Fig. 4. Part of the electrical schematics of the resistive sensor interface as a monostable circuit (see text).

total sampling frequency of 40 Hz. This means that each of the three joystick axis and each of the five force grasp sensors are sampled every 25 ms at most. Fig. 4 shows one of the eight resistance to time converters based on the monostable circuit principle. The variable resistor at left is the sensor (force sensor or joystick axis potentiometer). The fixed resistor in parallel and the capacitor are chosen as to obtain a maximum pulse duration of 2.5 ms. Each of the monostable circuits is independently triggered sequentially by the processor and the resulting pulse is measured by the microcontroller timer circuit. The complete schematics is given in the annex. For obtaining the listing of the firmware of the microcontroller, along with the custom virtual serial USB procotol, please ask the first author. By the way the software used on the personal computer is not available for public release.

In Fig. 5 the complete system is shown in operating condition fixed on a tablet hiding the joystick's mechanical part and the electronics. This prototype has been conceived for the right hand only and for right handed subjects.

III. CYBERNETIC APPROACH TO HUMAN PERFORMANCE EVALUATION

The word "cybernetics" comes from Greek "government" and, as Norbert Wiener[1] defined it in the 40's of last century, is "the scientific study of control and communication in the animal and the machine". As with the present case, cybernetics is applicable when the system being analyzed is involved in a closed signaling loop. This is originally referred to as a "circular causal" relationship or feedback. Although our system is concerned with feedback, it should be noted that we are not directly interested in a so-called "biofeedback" session. The term "biofeedback" is commonly associated with experiments or training or rehabilitation sessions in which a particular "output" of the human body, normally not appreciated at conscious level, is made known to the same subject through conversion to an appreciable acoustic of visual stimulus. Although in our case we are not so distant from a biofeedback session, nevertheless we prefer to deal with the term feedback of the motor control task instead (HIL model).

Fig. 5. Close view of the handle.

[1] Norbert Wiener (November 26, 1894 – March 18, 1964) American mathematician and philosopher.

At the base of the method there is our system prototype which allows the administering of a series of controlled motor-decisional tasks to the subject under test. The ultimate purpose is that of identifying the parameters of a mathematical model of the human controller [4].

Referring to Figs. 1 and 2 and neglecting the noises for simplification, the closed loop gain G_{CL} of the system is given as the ratio between the output (human system output in Fig.2) and the input (yellow target object position) as in the following:

$$G_{CL}(s) = \frac{H(s)}{1+H(s)M(s)} \quad (1)$$

where the laplace variable s is used permitting the evaluation of the system in the transient phase. In the steady state the frequency response can be used instead:

$$G_{CL}(j\omega) = \frac{H(j\omega)}{1+H(j\omega)M(j\omega)} \quad (2)$$

As the machine transfer function $M(s)$ is known, thus by measuring the input and output signals in the experimental set-up it is possible to identify the function $H(s)$ representing the human operator. This is done offline with the help of the function *ident* of the System Identification Tool of the MATLAB software.

IV. PRELIMINARY RESULTS

A typical linear human control function in a pursuit task like that depicted in Fig.2 is following:

$$H(s) = \frac{10e^{-0.2s}(1+s)}{(1+10s)(1+0.1s)} \quad (3)$$

As it can be seen in eq. 3, the function $H(s)$ is characterized by one zero (-1,0), two poles (-0.1,0) (-10,0) and a fixed delay of 0.2 sec. This is what it is likely to be expected based on our common experience. The fixed delay stands for the reaction time, the zero is coding our anticipation activity in doing a given movement and the two poles represent the cognitive elaboration and the muscular activation respectively. In this case the function $H(s)$ is defined by four numerical parameters that can be used as the input of a classifier based on human performances of subjects.

Coupled with a machine simulating an integrator performance:

$$M(s) = \frac{2}{s} \quad (3)$$

the resulting system presents a Bode plot as in Fig. 6 where the respective margins of stability (gain and phase) are shown.

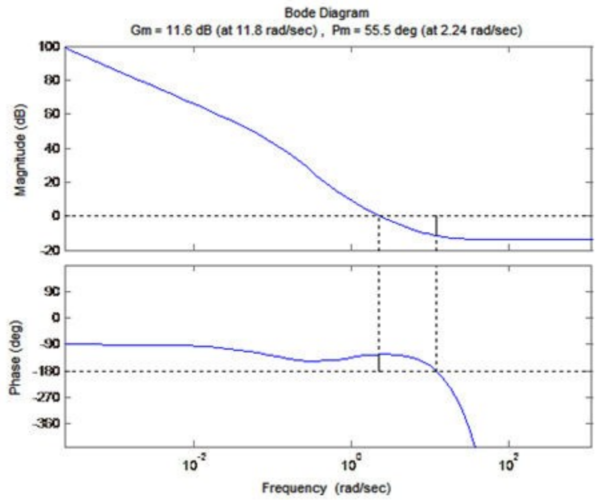

Fig. 6. Bode plot for studying the stability margins of the human control model.

V. DISCUSSION AND FURTHER RESEARCH

Although the theoretical foundations of this method for assessing human cognitive and motor performances were laid down so distant in time, the comprehension of this method by non-engineering researchers is still quite problematic.

The main problem experienced by medical personnel and researchers is that of being unable to disregard the anatomical and physio-pathological conditions of the subject while gaining a broader “eagle-view” of the actual situation. Medical people were educated to look for an anatomical or functional malfunction in the brain or muscles responsible for a given disability or impairment. With the proposed method the subject is considered, classified, and even diagnosed, as a black box whose performances in a standardized task are defined in terms of numerical parameters of a model function. This is a quite innovative point of view which has no or very few examples in the medical practice. Only a thorough campaign of research and measures on healthy as well as diseased subjects will be able to change this attitude of mind and eventually validate this proposition.

The strength of this method is in the possibility of numerically evaluate human performances while separating cognitive and peripheral functions. Should this method be validated, we will have means to quantitatively study healthy subjects, normal ones as well as athletes. We might infer and maybe we could stage neurodegenerative diseases or elderly subjects on the basis of their residual cognitive and motor performances.

Fig. 7. Preliminary tests with the instrument.

The possibility of studying the stability of the human control function might just open astonishing perspectives in the treatment and follow-up of Parkinson’s disease [5] [6]. That’s why this instrument is made open access to the public.

ACKNOWLEDGEMENTS

This is an ongoing work to which many people participated by adding various and different details to the original concept. The work of the students A. Vallet (B.Sc. engineering), L. Polverigiani (B.Sc. physio-therapy) and S. Mugnaini (Ph.D. rehabilitation engineering) is kindly acknowledged. Special thanks go to Mr. C. Guinchard (technical services of HEIG-VD), for his very important technical assistance, and to Dr. R. Vaswani (physiotherapist) for useful clinical discussions.

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ANNEX

(electrical schematics of the joystick control board)