Human Control Modeling Based on Multimodal Sensory Feedback Information

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Abstract. In order to simulate the human control behavior during a manipulation task in a remote controlled or in a X-by-wire systems, first it is necessary to measure and analyze the human control characteristics. The aim of this research is to measure the operator reaction time and analyze the human visual and force sensory feedback integration related to a manipulation task. Using the developed master-slave type experimental device it was possible to identify and build a human operator control model related to different sensory feedback. The human model related to visual feedback solely and visual/force feedback was identified using the techniques of system identification methods.

Keywords: Human-Machine Interface, System Identification, Reaction Time, Sensory Feedback Information.

1 Introduction

In order to simulate the human control behavior during a manipulation task in a remote controlled or in a X-by-wire systems, first it is necessary to measure and analyze the human control characteristics. The aim of this research is to analyze the human control characteristics in respect to the visual, force and audio feedback information and build a human control model that can also represent a control strategy based on multi-sensory feedback. This control model would be useful to assist the design, simulation and evaluation of human-machine systems like telerobots [1] and also computer assisted systems as power-assist and drive-by-wire vehicles. In this work the measurement of the reaction time will be compared to the time delay identified during a visual tracking task using only visual feedback and with force feedback information. An experiment device capable of measuring the human control characteristics in the presence of different sensory feedback information was developed.

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2 Human Control Model

Many studies in the area of visual tracking have been done to understand the human control characteristics due to visual feedback information. However, quite a few researches have been conducted in the field of force and audio feedback information with the objective of analyzing how the human operator makes use of this sensory feedback information in a manipulation task.

2.1 Visual Feedback

One result of McRuer [2] [3] works about the analytical theory on manual control of vehicles was the Crossover Model. See Eq. 1 and Fig. 1. According to the manipulated machine characteristics the human operator can modify his/her own dynamic characteristics so as the open-loop transfer function remains a first order system.

$G(s)$ represents the machine dynamics.

$$H(s)G(s) \approx \frac{\omega_c e^{-\tau s}}{s} \qquad (near \;\; \omega_c) \tag{1}$$

where, τ ($0.1 \sim 0.4$s) represents the time lag due to human responses, ω_c ($0.5 \sim 0.8$Hz) is the crossover frequency.

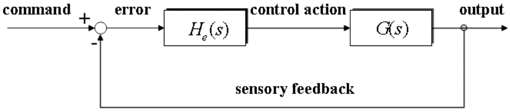

Fig. 1. Human Machine Block System

2.2 Force Feedback

The force feedback felt by the human operator is a result of a combination of tactile sensors and proprioceptive feedback. Although the individuals properties of each sensor have been studied, how the human operator uses those information and how they affect the human control characteristics are still not well known. However, it is of general agreement that the force feedback information is very important to identify the controlled object dynamics properties.

2.3 Audio Feedback

A primary function of audio feedback is said to direct the eyes to the source of the sound. More specifically in a tracking task the audio feedback provides information about the localization and velocity of the moving target. Although the space discrimination of auditory localization is not so accurate (about 15 degrees) compared to the visual, it provides supplementary information to assist other sensory feedback.

2.4 Human Control Model Based on Multimodal Sensory Feedback

This work proposes a human control model based on multiple sensory feedback information. (See Fig. 2). The human control characteristics related to visual, force and audio feedback information will be measured separately and then a combination of different sensory feedback will be analyzed in order to understand how the human operator uses these sensory feedback information to acquire an internal model of the controlled machine. First, in this work, the analysis of the human control strategy in the presence of visual, force and the combination of visual and force feedback information was conducted.

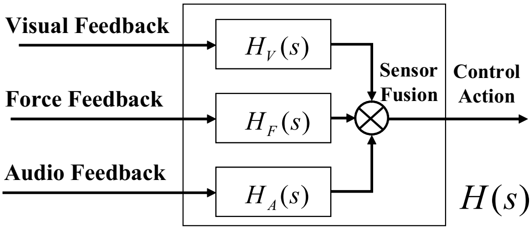

Fig. 2. Multimodal sensory feedback scheme

3 Experiments

Two types of experiments were conducted. First, the human reaction time was measured. The second experiment is based on visual tracking in the absence and presence of force feedback. The proposal for this study was reviewed by the Institutional Committee for Ergonomic Experiments and approved by the Director of Safety and Environmental Protection Department.

3.1 Reaction Time Experiment

Before conducting the operator model identification experiments, each subject's Single Reaction Time (SRT) and Choice Reaction Time (CRT) were measured to be compared to the time delay obtained from the second experiment. During this experiment the forearm pronator and supinator muscles EMG was also measured.

Single Reaction Time (SRT). In the SRT experiment the subject was instructed to turn the dial after the visual cue, which is a LED source, is presented. The instructed direction of rotation was clockwise (CW). The visual cue is presented in a random time between 3s and 9s after the go signal. After some training each subject executed 10 trials.

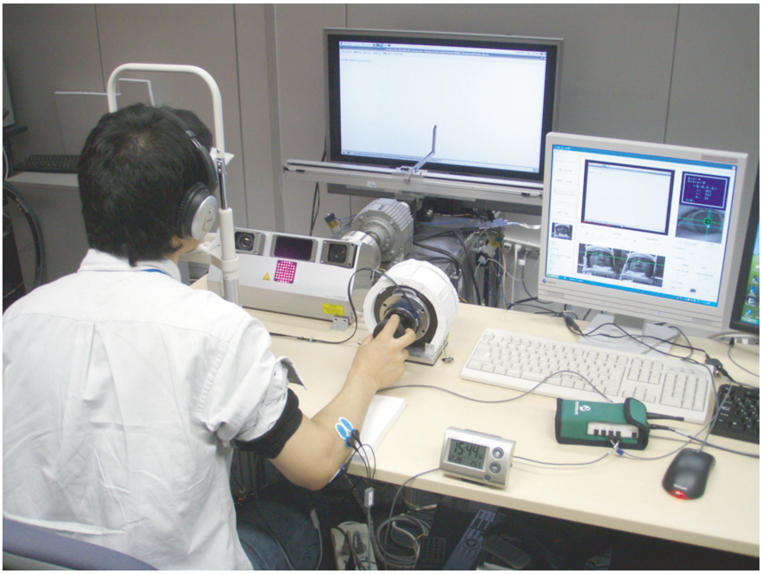

Fig. 3. SEesaw Experimental Device (SEED)

Choice Reaction Time (CRT). In the CRT experiment the subject has to turn the dial in the CW direction if the right visual cue is presented or in counter clockwise (CCW) direction if the left LED turns on. The side, right or left, and the visual cue presenting time is showed randomly to the subject. After become familiar with the task each subject performed 20 trials.

SRT and CRT Results. The results of the SRT and CRT experiments are shown in Table 1. In both SRT and CRT experiments the reaction time was defined as the time necessary to the subject rotate the dial more than 45 degrees after the visual cue was presented. The subject A was the fastest and the subject B had the slowest response. The difference between these 2 subjects can be attributed to the time necessary to perceive the visual cue and send the motor commands to the muscles since the starting of EMG activation differs greatly between subjects. (See Fig. 4 and Fig. 5). The time necessary to process the visual cue information and send motor command to the muscles varied from 0.15s to 0.29s in SRT experiment and was between 0.19s to 0.34s in CRT experiments. Thus it can be inferred that the time need to decide which direction to move was between 0.04s to 0.15s. On other side, there were no much difference among subjects in the time between the muscle activation and movement onset which corresponds to 0.02s - 0.05s. These results demonstrate that the cognition and decision making are responsible for great part of the human response delay.

3.2 Operator Control Characteristics Identification Experiment

The method to model the human operator adopted in this study is based basically in the system identification used in control theory. However, it is crucial

Table 1. Results of SRT and CRT Experiments (mean ± SD)

Experiment	Subject A	Subject B	Subject C
SRT [s]	0.29 ± 0.03	0.38 ± 0.05	0.32 ± 0.03
CRT [s]	0.34 ± 0.04	0.46 ± 0.07	0.38 ± 0.05

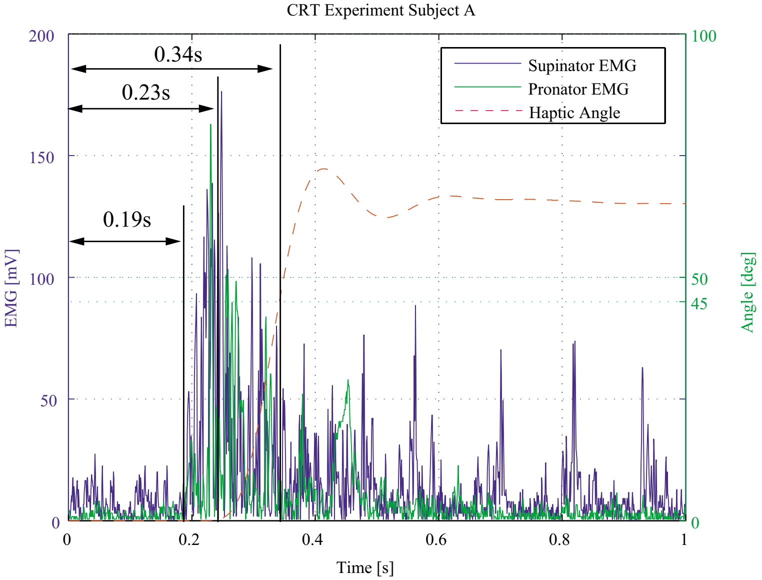

Fig. 4. CRT experiment subject A (fastest). The EMG activation before the movement actually started can be noticed.

to select a task that can provide an analysis of the operator characteristics in a visual and force control manipulation independently, i.e. a task that can be performed with only one type of sensory feedback information. It is also preferable to be a continuous task for system identification analysis in a wide frequency range. The peg-in-hole task is widely used as an example of robot control, but it is very hard to decompose the position and force control strategies. The inverted pendulum is also commonly used to demonstrate different control methods. However, it is a task very difficult to accomplish with the eyes closed. After considering many tasks performed by a human operator, the control of a slider on a seesaw was chosen as a suitable task that can pull together all the necessary features to analyze and identify the human-machine system related to visual, force and also audio feedback information independently. To analyze the human control characteristics related to different sensory feedback properties a master-slave type SEesaw Experimental Device (SEED) was developed. The master haptic device consists of a dial with a force sensor and the slave is an actuated linear guide that works as a seesaw bar with a slider over it. (See Fig. 3 and Fig. 6). After

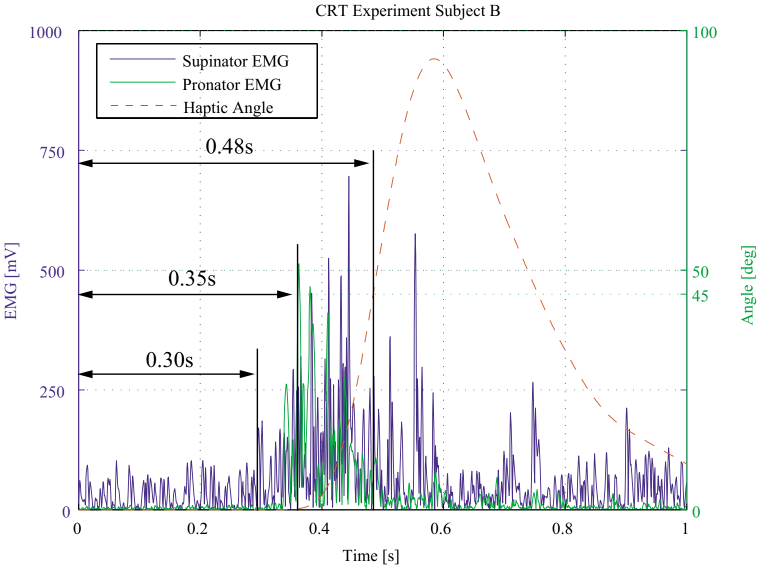

Fig. 5. CRT experiment subject B (slowest). The starting of the EMG activation ocurred later than the time compared to the fastest subject.

analyzing the control characteristics based on visual ($H_v(s)$), force ($H_f(s)$) sensory feedback information separately, the combination visual and force feedback ($H_{vf}(s)$) was analyzed.

Visual Pursuit Tracking with a Normal Slider. In this first experiment to analyze the human visual feedback properties, the human operator manipulates the master dial in order to make the slider, PD controlled, follow a random reference signal displayed in a monitor. The machine characteristics is a first order system. After 20 training trials, 10 trials were measured. Fig. 7 shows the reference signal, the measured data and the output of the identified operator model. The technique used to identify the human operator's characteristics is common to all the following two experiments. First, it was assumed that the human-machine open loop transfer function has the generalized form of Eq. (2).

$$H(s) = K\frac{(1+T_L s)}{(1+T_I s)}e^{-\tau s} \tag{2}$$

where K represents proportional gain, $e^{-\tau s}$: time delay due to human response, $(1+T_L s)$ is the lead time constant (relative rate-to-displacement), $(1+T_I s)^{-1}$ is the lag time constant.

Using the process model identification of Matlab toolbox the appropriate parameters were calculated by minimizing the error between the model output and the measured data. By this search the most suitable form was selected and then the time delay which corresponds to the smaller fitting error was explored. In all

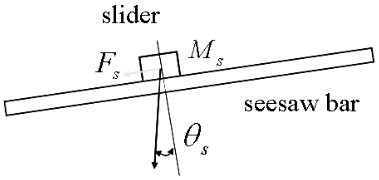

Fig. 6. Seesaw and slider model

the cases a priori knowledge about the controlled machine was used in order to obtain the operator characteristics. After obtaining the parameters, they were averaged separately and the results are shown in Table 2.

Visual Feedback using a Seesaw Task. Here the subject is instructed to follow the random reference signal as the previous experiment. But this time the machine dynamics behaves as a slider over a seesaw, i.e. like Eq. (3). There is no force feedback. After some practice the subject is able to execute successfully the task. To avoid the subject to notice that the slider behavior corresponds to a seesaw task, the seesaw bar was maintained in horizontal position.

$$(\theta_s \approx 0 \Rightarrow sin\theta_s \approx \theta_s) \qquad G(s) = \frac{x_s}{\theta_s} = \frac{g}{s^2} \tag{3}$$

where g is the gravity, θ_s is the seesaw bar inclination, x_s is the slider position and s is the Laplace operator

Visual and Force Feedback using a Seesaw Task. In this task the subject has to follow a random reference signal feeling the torque caused by the dislocation of the slider over the seesaw. The proficiency in the task execution was similar to the visual feedback solely, but the human modeling error increased due to the need of extra operational force. (Fig. 9).

3.3 Human Control Characteristics Experiment Results

The results of identified human control characteristics are shown in Table 2. The human control model related to visual pursuit task showed a first order

Table 2. Identified Human Control Model

Experiment	Subject A	Subject B	Subject C
Pursuit $H_p(s)$	$\frac{2.3}{1+0.4s}e^{-0.20s}$	$\frac{2.1}{1+0.6s}e^{-0.27s}$	$\frac{2.2}{1+0.5s}e^{-0.22s}$
Visual $H_v(s)$	$6\frac{1+4s}{1+0.06s}e^{-0.24s}$	$4\frac{1+4s}{1+0.2s}e^{-0.31s}$	$10\frac{1+2s}{1+0.03s}e^{-0.21s}$
Visual/Force $H_{vf}(s)$	$10\frac{1+2s}{1+0.04s}e^{-0.23s}$	$8\frac{1+2s}{1+0.1s}e^{-0.29s}$	$13\frac{1+2s}{1+0.04s}e^{-0.22s}$

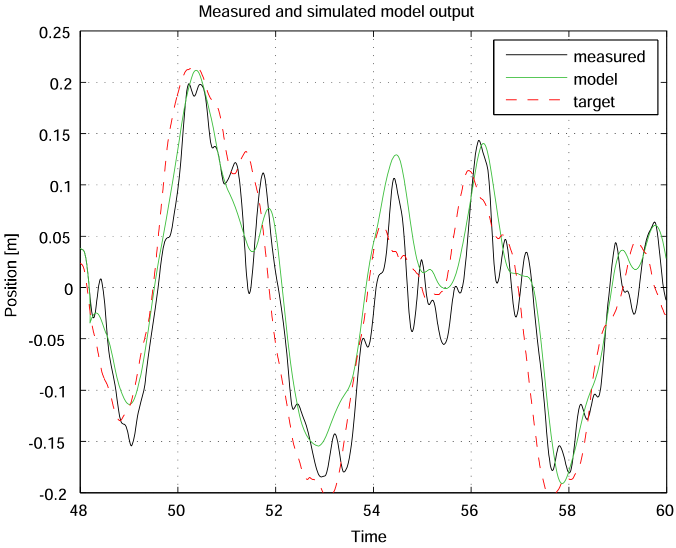

Fig. 7. Visual pursuit experiment

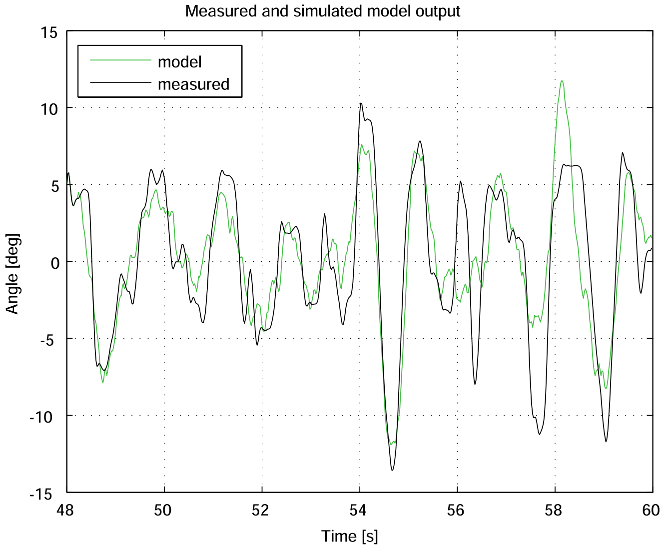

Fig. 8. Seesaw task experiment using only visual feedback information

characteristic. Comparing the three subjects it can be noticed that the lag time element T_I is proportional to the correspondent time delay τ . Fig. 7 shows the reference target, the measured data and the control model output of the identified mean human model. The model output has the same behavior of the human operator except the high frequency features.

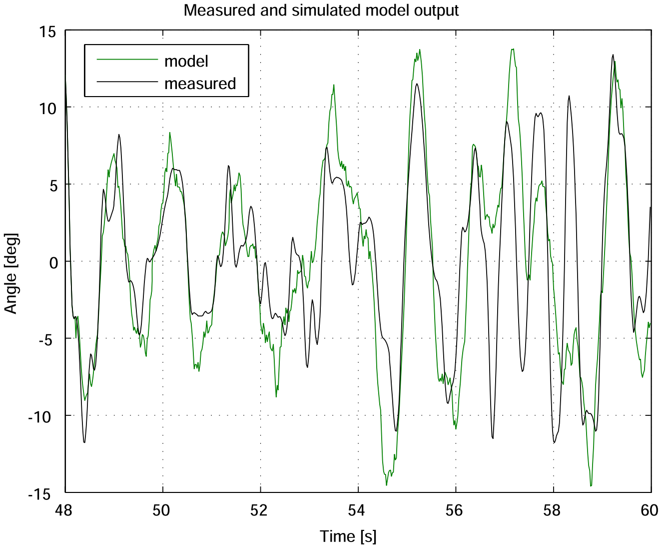

Fig. 9. Seesaw task experiment using visual and force feedback information

In the case of seesaw task using visual feedback with or without the presence of force feedback, all the subjects presented a lead time element T_L. This lead time element is responsible for the prediction of the slider's behavior. Due to the high acceleration of the gravity, a predictive element was necessary to make possible the control by the human operator.

The presence of force feedback had the effect of decreasing the time constant and increasing the gain element. The latter one can be attributed to the high stiffness of the forearm because of the haptic feedback.

4 Discussion

From Table 2, it can be noticed that according to the characteristics of the task the time delay identified has different values. But the relation between subjects is preserved as the subject B has the biggest time delay. Although the time delay is different from the RT experiment results, the direct measurement of the human response time presents a reasonable and practical method of identifying the time delay reducing the number of parameters to be fitted. Further investigation about the muscle activation time and neuromuscular dynamics should be conducted to achieve a better estimation of the human response delay.

5 Conclusion

This research proposed an analytical method using the SEED to identify the human control characteristics related different sensory feedback information. The human model related to visual feedback solely and visual/force feedback was identified using the techniques of identification methods. It is important to notice that all the experiments were performed without audio information. The next step is to build a human sensory feedback integration model to represent the human operator including also the audio feedback information. These sensorial feedback information are believed to play an important role in the acquisition of the internal model of manipulated machines. Future work will be done to analyze how the human model could be decoupled in feedforward, representing the internal model, and feedback elements.

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